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PERSPECTIVES IN TECHNOLOGY

Solar Energy 2

K.S.C.S.T.

PERSPECTIVES IN TECHNOLOGY

Vol. 2 **Solar Energy 2**

Editor: Solar Energy 2

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Perspectives in Technology is a manual produced by the Karnataka State Council for Science & Technology for the faculty and students of engineering colleges of Karnataka. Each issue shall concentrate on one sector of engineering. Copies of Perspectives in Technology, can be acquired by writing to the Secretary, KSCST, Bangalore-560 012.

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1. Editorial

The Student Projects Programme (SPP) has now entered the seventh year. The main objective of the SPP is to channel student projects into areas relevant to the development needs of the State, and in particular to those of the rural areas. Through the SPP, the KSCST has set up linkages with centres of science and techology outside Bangalore, like Mysore, Mandya, Gulbarga, Hubli, etc. Through this mechanism it has been possible to harness the tremendous potentialities of the students and faculty of the Engineering Colleges of the State. This has largely been due to the cooperation of the faculty of the engineering colleges and the faculty of Indian Institute of Science, Bangalore in particular from ASTRA (Centre for Application of Science and Technology to Rural Areas). An analysis and review of the SPP projects carried out over the last few years has revealed that the large number of projects has to a certain extent hindered the monitoring of SPP projects. Consequently, it has become difficult to get the details of work done by several batches of students in a particular area. The SPP projects undoubtedly constitute a source of enormous information; however, it has to be moulded into an information system to be utilised by resource persons, faculty, and the past and present students of engineering colleges.

The SPP projects have covered many sectors, viz., Indusry, Energy, Education, Agriculture, Water and Irrigation, Health and Nutrition, Housing, Ecology and Environment. The SPP has now been extended to the field of medical education, and ten projects in various branches of medical have been sanctioned for the year 1984-86.

The SPP has many achievements to its credit. It has stimulated a large number of students and faculty to think of the problems of their immediate surroundings and to use their knowledge and training to improve the environment. Through involvement with live situations and real problems, the SPP has created an excitement and a challenge which has contributed to accelerated learning and an enhancement of the quality of education.

The SPP depends for its success on the availability of high-calibre resource persons. To secure the commitment of such persons, it is essential that the faculty of the engineering colleges have access to the facilities and also the expertise in institutions of advanced learning. At the same time, the scientists and engineers of the better endowed institutions would involve themselves with, and assist, undergraduate institutions.

This manual is the first step in that communication process. Topic by topic, area by area, and sector by sector, the manual will deal with the fundamentals and state-of-the-art of the technology, a review of the SPP projects in the field, and a statement regarding what needs to be done. It will ensure contact between students and faculty in undergraduate institutions and researchers in post-graduate institutions through articles and questions and answers. Hopefully, it will increase the band of resource persons available to the SPP. Above all, it is intended to make students taking SPP projects feel that they are backed by a great deal of knowledge and a team of experts.

Whereas, the first issue of the manual was concerned with solar energy and the design and fabrication of flat-plate collectors, this issue is concerned with other solar powered devices such as solar concentrators, cookers, stills, ponds and engines. A later issue of the manual will be devoted to solar refrigeration and photovoltaic devices. The treatment of the

subject matter has been largely algorithmic and partially analytical – so as to enable students to successfully arrive at the designs of whatever solar energy device they are interested in. The analytical portion is an aid to understanding the deficiencies, drawbacks and limitations of the system designed and/or fabricated.

Students and faculty interested in knowing more about these devices are recommended the texts mentioned in the bibliography at the end of each chapter.

—Shri M. A. Sethu Rao

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2. Solar Concentrators

2.1 Introduction

Concentrator type solar collectors have caught man's fancy from time immemorial. From the first observation of dry twigs and grass being set on fire by an accidental concentration of the sun's rays on them by droplets of dew, man has tried to use his ingenuity to concentrate the sun's rays. The feasibility of concentrating sunlight to obtain high temperatures was recognised as far back as the Mesopotamian era, when temple priestess' used polished golden vessels to light alter fires. However, the most famous application of solar energy in the ancient world was that of Archimedes (circa 212 B.C.), who is reported to have set fire to an invading fleet by directing sunlight reflected from the polished shields of his soldiers on to the masts of Roman ships. Much later, Joseph Priestley, prepared oxygen for the first time by heating potassium perchlorate by concentrating sunlight with a lens. The French chemist Antoine Lavoisier used a solar concentrator consisting of a lens to provide the "purest heat source possible". With this device he was able to reach temperatures high enough to melt platinum (1760K). More recently, even refractory materials have been melted down in the famous solar furnace built in the Mount Pyrenees of Odeillo, France. The world's largest solar experimental facility is the 5MW thermal test facility at Sandia Laboratories at Albuquerque, New Mexico, where 220 computer controlled heliostat mirrors (each of area$=37.2\ m^2$) convey about 5 MW of solar energy onto a target area, on top of a 61m tower so as to produce a peak intensity of about $2.5 MW/m^2$, that corresponds to a black body emitter of temperature 2570K.

Many drawbacks that beset the flat-plate collectors do not affect concentrators. As the name implies, the concentrator works by concentrating solar energy of very dilute power density (less than $1 kW/m^2$) to a much higher value - anywhere from a few percent to several hundreds or a thousand times that of the initial $1\ kW/m^2$. Such a high degree of concentration results in high power densities able to yield temperatures as high as 4000K or more. The temperature of the sun is nearly 6000K and this sets an upper thermodynamic limit to the temperature that can be obtained. It is apparent that the thermal efficiency of any device converting solar energy to work would greatly improve by using a concentrator, since the Carnot efficiency is directly related to the temperature of the source ($\eta_{carnot}=(T_1-T_2)/T_1$, where T_1=temperature of the source, and T_2=sink temperature). For example, a solar engine coupled to a flat-plate collector with a peak temperature of 375K would give an ideal maximum efficiency of 20 per cent, while a concentrator yielding a working fluid at 1000K would give a maximum efficiency of nearly 70 per cent. The actual cycle efficiencies would be much lower. While concentrators have many attractive features there are several disadvantages also. In this chapter we shall briefly examine the common types of concentrators in use and study their performance and operational characteristics.

2.2 General features of concentrator type collectors

A concentrator has either a reflective or refractive device which directs the solar radiation falling on its aperture, on to a receiver or absorber whose area needs to be much smaller than the aperture of the collector - the reflective or refractive device. With a flat-plate device the area of the absorber is the same as the aperture. In comparison to flat-plate collectors, concentrators have many advantages and drawbacks. Some of these are listed below.

2.2.1 Advantages

1. The collection of solar energy is effected by reflective surfaces which require less material to fabricate (since they can be very thin) and are hence structurally lighter.

2. Absorber area is smaller and hence heat losses are smaller. Secondly, since the intensity of radiation is much higher, T_{rec} the receiver temperature, is higher.

3. Selective coatings on the absorber can reduce radiation losses, while evacuation of the absorber can reduce convective losses.

4. Since the size of the absorber is much smaller in comparison to flat-plate collectors, both selective coatings and evacuation of absorber can be done at a relatively low cost.

5. Higher temperature implies a higher thermodynamic efficiency for doing useful work.

6. Higher temperature allows more heat storage per unit volume, hence lower cost for storage.

2.2.2 Disadventages

1. Collection of diffuse radiation is either negligible or very low, depending on the field of view of the collector, and whether the concentrator geometry is of the imaging or non-imaging type.

2. Tracking of absorber and/or reflector is required.

3. Degradation of reflector material occurs with time, with consequent deterioration of performance.

4. Tracking of huge areas requires tracking devices and complex structural requirements.

2.2.3 Concentration Ratio

For a concentrator the energy balance is (see eq (1) ref [1], ch. 3)

$$q_u = \eta_{opt}\, I_b\, A_a - U_c\, (T_c - T_{amb})\, A_r \qquad (1)$$

$$\eta_{collector} = q_u/(I_b A_a)$$
$$= \eta_{opt} - U_c\, (T_c - T_{amb})\, (A_r/A_a)/I_b \qquad (2)$$

A_a is the aperture area of concentrator (or collector), A_r is the area of receiver (or absorber), η_{opt} is the efficiency of optics, A_a/A_r is the Concentration Ratio=CR. CR$\sim$1 for flat-plates ; CR$>$1 for concentrators.

Since, $A_r/A_a = 1/CR < 1$, $\eta_{collector}$ for concentractors can be higher than that for flat-plates. Although in principle it should be possible to obtain an infinite degree of concentration (and hence infinite power density and temperature) by reducing the area of the receiver A_a to zero, such a situation does not arise in practice. There is a certain minimum area of the receiver that is decided by the size of the source and the geometry of the concentrator. Of course, it is thermodynamically impossible to take the radiation from a source that is in thermodynamic equilibrium and concentrate its emission to achieve a temperature higher than that of the source. (N. B. The radiation from a non-equilibrium source like a laser can however be concentrated to yield temperatures of millions of degrees ; as has been demonstrated in fusion lasers).

2.2.4 Thermodynamic limits to Concentration [2]:

To obtain an estimate of the upper limit of concentration possible with solar radiation, a simple analysis is carried out here. Consider a simple concentrator shown schematically in the Fig. 2.1.

For such a collector : $A_s\, F_{sa} = A_a\, F_{as}$;

and, $A\, F_{sr} = A_r\, F_{rs}$ (3)

where, F_{ij} is the view factor for the surface i, for viewing surface j, which is equal to fraction of energy leaving i that is actually incident on j

Then, CR=concentration ratio$=A_a/A_r$

$$= F_a\, F_{rs}/(F^a{}_s F_{st}) \qquad (4)$$

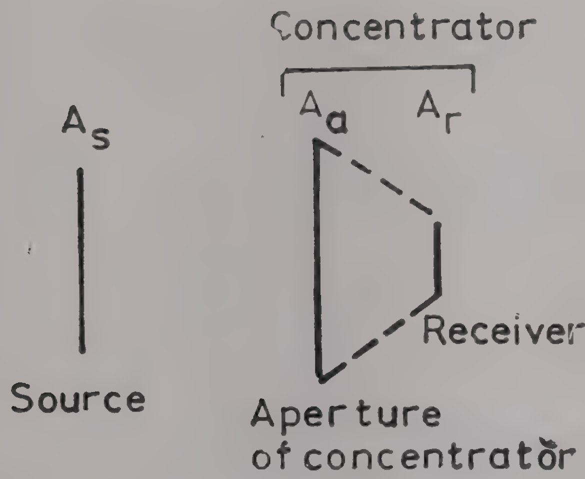


Fig. 2.1 Schematic diagram of concentrator

Assuming that all the energy collected by A_a is incident on A_r (*i.e.*, a perfect concentrating collector), we have
$F_{sa}=F_{sr}$ and $CR=F_{rs}/F_{as}$.

Since, $F_{rs} < 1$, $(CR)_{max}=1/F_{as}$. (5)

The source (sun) brightness per unit solid angle is preserved in any optical system, i. e. B′ (T) at the focus is the same as B (T) at the sun. So the amount of energy in a solid angle of any optical system at its focus, B′(T) is related to that emitted by the surface of sun in 2π solid angle by the relation :

$$B'(T)=B(T)\ \{\tfrac{1}{4}\ \mathrm{Sin}^2\ \Phi\} \tag{6}$$

where Φ is the rim angle of the concentrator. This means that for an image to have the brightness approaching that at the surface of the sun (i. e. T=5760K) the optical system has to have $\Phi=90°$ (see Fig. 2.2). Thus for a paraboloid whose rim angle $2\Phi=180°$, whose aperture is arbitrarily assummed to be 100 units, and a Fresnel lens with a facet angle of 60°, Φ turns out to be only 42°, and $\sin^2\Phi=0.45$, with the result that with the same physical aperture for both the paraboloid and Fresnel lens, the relative aperture of Fresnel lens will only be 0.45. The energy losses in transmission through the atmosphere, imperfections in the reflector surface, etc., cause the effective

temperature to be much lower than the ideal. Figs. 2.3 and 2.4 show what is normally achieved in practice.

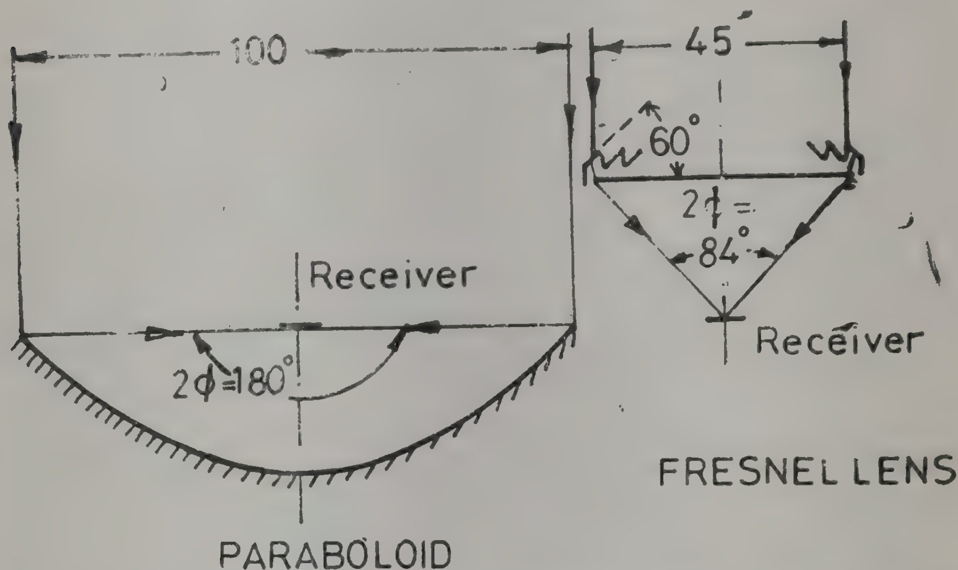


*Fig. 2.2 Comparison of Relative Aperture limits for a **Paraboloid** and Fresnel Lens*

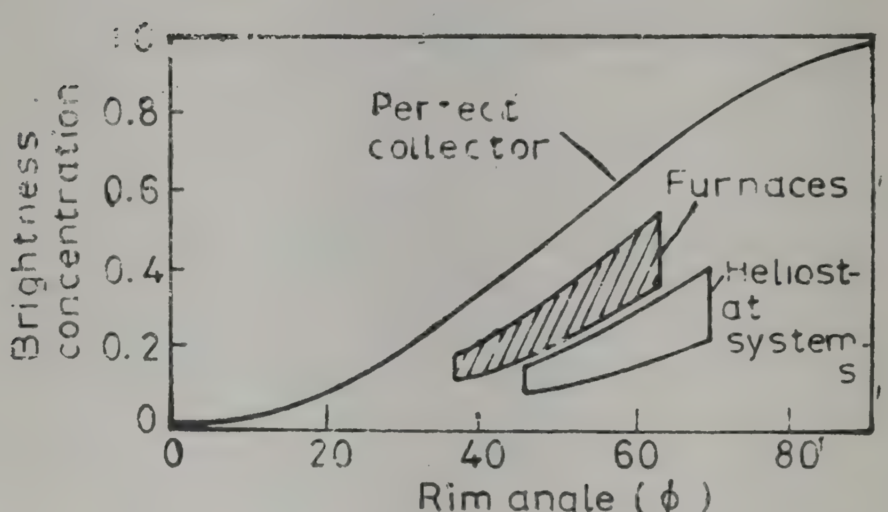


*Fig. 2.3 Brightness concentration for a Paraboloid/Fresnel **Lens** (point focus type collector) for a perfect collector* $\theta=90°$

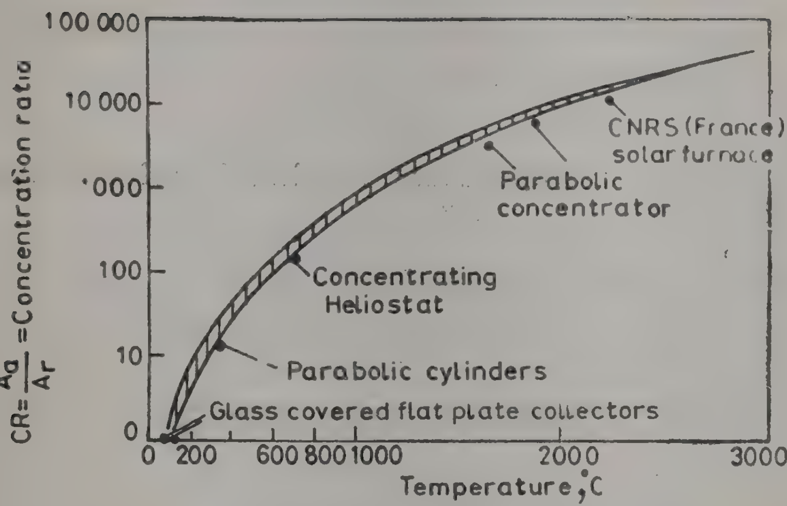


Fig. 2.4 Typical temperatures attainable with concentrating type collectors

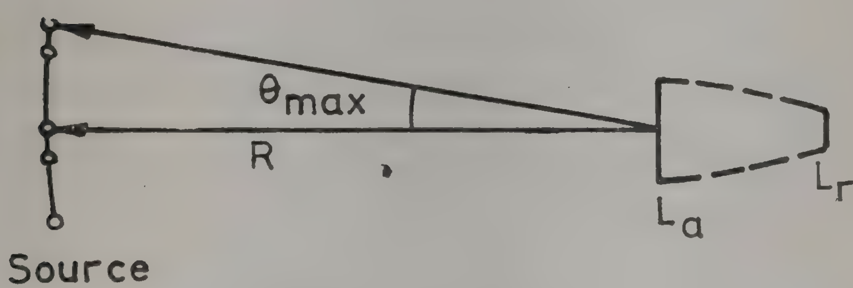


Fig. 2.5 A two dimensional concentrator, acceptance half angle θ_{max} and several positions of sun

For a 2 dimensional concentrator, (see Fig. 2.5), that concentrates the radiation along a line rather than at a point as a 3 dimensional concentrator does, we have $F_{as}=F_{sa}\ (A_s/A_a)$ when $R \gg 1$, $F_{as}=\sin\theta_{max}$, the angle θ_{max} is the "acceptance half-angle", which denotes the angular zone within which radiation is accepted by the concentrator.

So, $(CR)_{max}=1/[\sin\theta_{max}]$ (7)

Practical limits on θ_{max} range from $>1/4°$ - the minimum required for covering the sun's disk (which subtends a half

angle of 1/4° at the earth) to 180° - which is the value for a flat-plate accepting radiation from the entire upper hemisphere. For a 3 dimensional concentrator $(CR)_{max}=1/[\sin^2 \theta_{max}]$

2.2.5 Maximum temperature attainable with concentrators

Although ideally it is possible to reach the sun's temperature at the focus, practical limitations make the maximum temperature attainable at the focus much lower. The maximum temperature attainable in a real concentrator is estimated next.

For a three dimensional concentrator :

$$q_{abs}=\tau\alpha\,[A_s\,F_{sa}\,\sigma T_s^4]=\tau\alpha\,[A_a\,F_{as}\,\sigma T_s^4]$$
$$=A_a \sin^2 \theta_{max}\,(\sigma T_s^4) \qquad (8)$$

Since the sun's disc subtends a half angle of 1/4°; $(\theta_s \sim 1/4^\circ)$, $\theta_{max}=1/4^\circ$ for the best concentrator. When no useful energy is extracted from the absorber the maximum temperature occurs. A simple energy balance gives, $q_{abs}=q_{losses}$. Losses in the absorber are due to radiation, convection and conduction, i.e.

$$q_{losses}=\varepsilon_{ir}\,A_r\,\sigma T_r^4+\text{convection}+\text{conduction}$$
$$=\varepsilon_{ir}\,A_r\,\sigma T_r^4 \qquad (9)$$

assuming that the absorber is kept inside an evacuated enclosure, so that convection losses are small.

Energy balance on receiver :

$$q_{abs}=q_L+\eta_c\,q_{abs} \qquad (10)$$

where η_c is the fraction of absorbed energy that is transferred to the working fluid, then

$$(1-\eta_c)\,\tau\alpha\,A_a \sin\theta_s\,\sigma\,T_s^4=\varepsilon_{ir}\,A_r\,\sigma\,T_r^4 \qquad (11)$$

$$T_r=T_s\{(1-\eta_c)\,\tau(\alpha/\varepsilon_{ir})\,(A_a/A_r)\,(1/\sin^2\theta_s\}^{1/4}$$
$$=T_s\{(1-\eta_c)\,\tau\,(\alpha/\varepsilon_{ir})\,(CR/CR_{max})\}^{1/4} \qquad (12)$$

In the limit $T_r \to T_s\,(CR/(CR)_{max})^{1/4}$; i.e. $T_r < T_s$,
for a two dimensional concentrator: $CR_{max} = 1/\sin\theta_s = 1/\sin(1/4°)$

$$\simeq 0(200) \qquad (13)$$

for a three dimensional concentrator : $CR_{max} = 1/\sin^2(1/4°)$

$$= 1/\sin^2(\theta_s) \backsim 0(40000) \qquad (14)$$

For actual concentrator type collectors (reflective type) the values of CR obtainable are: (a) for cylindrical concentrators CR varies between 1 to 100, (b) for conical concentrators CR can go upto 120, (c) while for paraboloid concentrators CR can go upto 10,000 or more.

Refractive optics can also be used. The only practical refractive type concentrator is the Fresnel lens.

2.2.6 Optical limits to concentrators

As mentioned earlier the job of the optical device in the concentrator is to receive the solar radiation arriving over a large area (the aperture area) and then to relay this with as little degradation as possible to a smaller area where an absorber (receiver) can be placed. If the area of this receiver can be made as small as possible then the power density gets enhanced and hence higher temperatures can be achieved. If the concentrator is made to track the sun continuously then it is possible to obtain an image of the sun using an optical reflector or refractive device (like the lens) whose size is limited only by the extent of the source. Thus very high concentration ratios (close to the ideal limit of $1/\sin^2(1/4°)$) can be obtained for such devices. However, if in the interest of simplicity tracking is not desired the obtainable concentration ratios fall off rapidly. For example, if a simple trough like device (2 dimensional concentrator) is oriented in the north-south direction and tilted so that the place of sun's virtual motion is normal to the aperture, then the aperture and acceptance angle have to be fixed so as to collect solar radiation over a specific period. For collection over an 8 hour period in a

day one would need an acceptance half angle of 60 ($15^\circ \cdot 8/2$), so that $CR_{max} = 1/\sin 60^\circ = 1.15$.

If on the other hand the concentrator is oriented along the east-west direction then the acceptance angle is limited by the profile angle excursion from the summer solistice to the winter solistice. The profile angle is given by

$$\tan\gamma = \tan\propto/\cos a \tag{15}$$

where a is the solar azimuth angle and $\propto$ is the solar attitude angle given by : $\sin \propto = \sin \delta \sin L + \cos \delta \cos L \cos h$ (16)

$$\cos a = (\cos \delta \sin h)/\cos \propto \tag{17}$$

(see Fig. 2.2 to 2.4 in chapter 2 Ref [1] for the definition of solar angles).

Thus for Bangalore ($L = 12^\circ 58'$) the profile angle γ at 4 p.m. or 8 a.m. on the summer solistice(June 21, $\delta = 23^\circ 27'$) is γ ($h = 60^\circ$, June 21) $= 34^\circ$ (18)

While on the winter solistice day (Dec. 22, $\delta = -23^\circ 27'$)
γ ($h = 60^\circ$, Dec 22) $= 24.3^\circ$

Hence the total excursion of the sun is (34-24.3) 10°. For collecting solar radiation over this range, without tracking, for a trough like collector placed east-west the maximum CR is

$$CR_{max,\ EW} = \frac{1}{\sin\ (10/2)} = 11.5$$

This is assuming the solar collection is required over 8 hours (symmetrically about the solar noon) per day. Fig. 2.6 shows the range of acceptance angles for the solistices and equinoxes. If the latitude is further north (say $L = 25^\circ$),
γ ($h = 60^\circ$, June 21) $= 36.3^\circ$ and γ ($h = 60^\circ$, Dec. 22) $= 17.3^\circ$ i.e., total excursion of γ has to be $(36.3 - 17.3) = 19^\circ$ and the $CR_{max,\ EW} = 1/\sin\ (19/2) = 6.06$

While for $L = 40^\circ$, γ ($h = 60^\circ$, June 21) $= 91^\circ$ and γ ($h = 60^\circ$, Dec. 22) $= 9.1^\circ$, and excursion in $\gamma = 82$, or $CR_{max,\ EW} = 1.53$

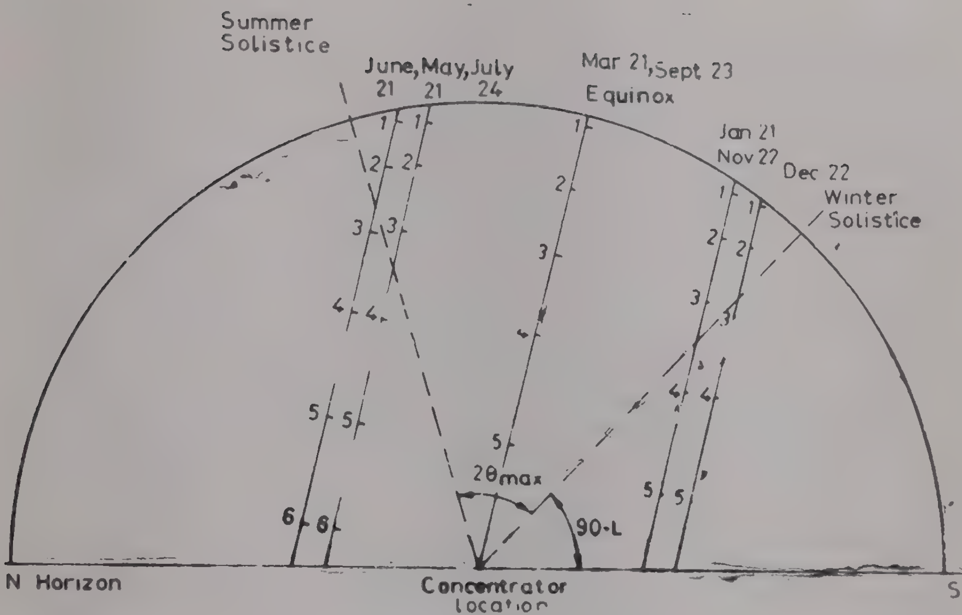


Fig. 2.6 Profile angles of sun at different times of year showing hours of collection, for a collector with $2\theta_{max}=60°$ $(CR \backsim 2)$. Numbers are time in hours from local solar noon. At solistice nearly $5\frac{1}{2}$ hours of collection is possible.

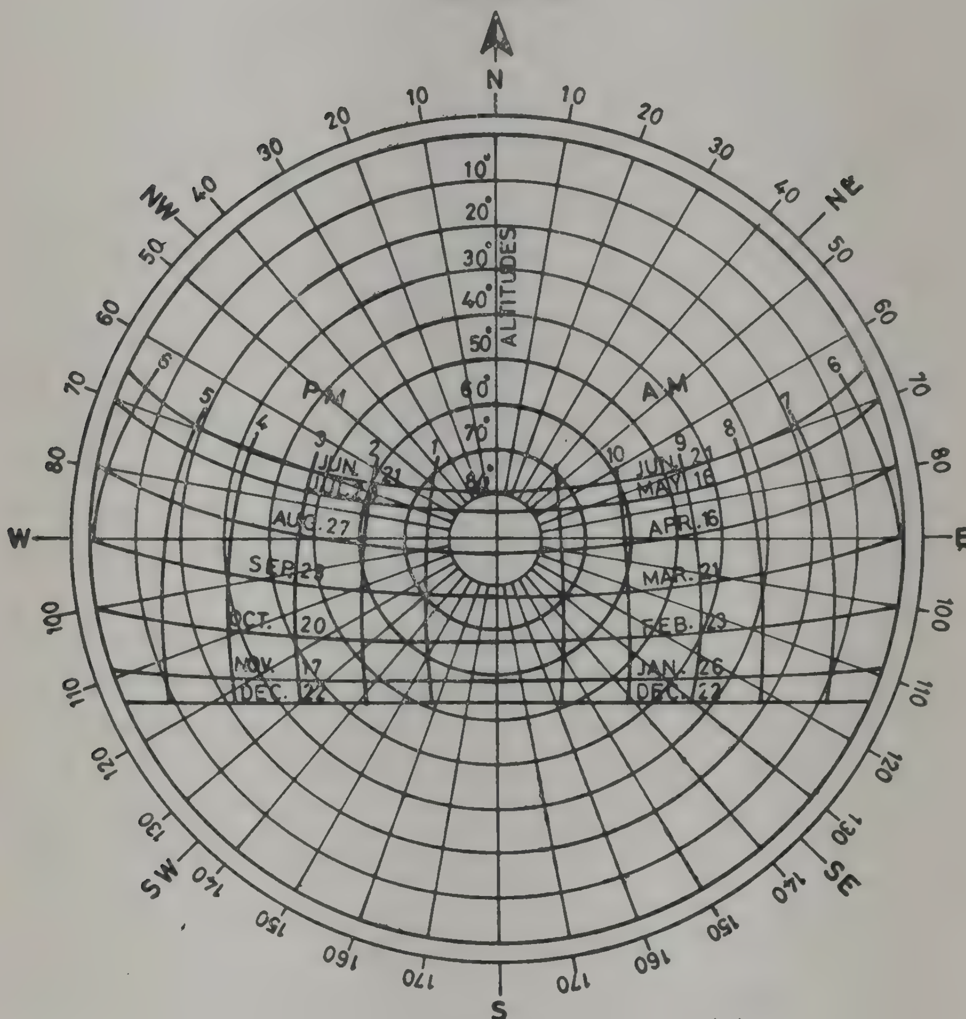
From Fig. 2.6 it is seen that by changing the acceptance angle of the collector, the period of collection can be changed and that, at times other than the solistices, collection over longer periods is possible for a given acceptance angle. The values of $\propto$ and a can be easily obtained by using "the sun path" diagrams, like that depicted in Fig. 2.7 for each latitude.

2.2.7 Collection of diffuse radiation

The above consideration is only valid for the beam component of solar radiation. Since a large fraction (>10%) of the total radiation is diffuse it is important to know how diffuse radiation is collected. It is possible to show that only a fraction (1/CR) of the diffuse radiation incident on the aperture of the concentrator reaches the receiver if the diffuse radiation is totally isotropic. But in practice a fraction greater than this is usually collected since the diffuse radiation is not

totally isotropic, but is concentrated near the solar disk except during highly clouded days.

SOLAR CHART



LATITUDE 13° NORTH

Fig. 2.7 Sun path diagram showing positions of the sun (altitude and azimuth angles). The declinations are $\delta = 23.5$ June 21, 20° May 16, 10° Apr. 16, 0° Mar. 21, –10° Feb. 23. -20° Jan. 26, -23.5° Dec. 22

2.2.8 Tracking requirement

As seen from the analysis, the tracking requirement depends on the acceptance angle θ of the concentrator. The larger the θ, the lesser the tracking requirement. So it is possible to have either totally fixed or intermittently adjusted devices with large acceptance angles. For higher CR's, continuous tracking is essential. If the reflector is oriented east-west the tracking is over approximately $\pm 30°$/day, while a north-south orientation requires a 15°/hour movement. In both these situations a declination excursion of $\pm 23.5°$/year is to be taken care of.

2.3 Reflective types of concentrators

Concentration of solar radiation becomes essential when a working fluid temperature above that typically obtainable with flat-plate collectors (say 80°C) is desired. Mirrors either flat or curved with single or multiple curvature are arranged in an enormous number of ways, to reflect the solar radiation falling over them, to an absorber placed at a suitable position within an enclosure ; commonly a well insulated vessel surrounded by a glass jacket to cut down heat losses. The principal consideration in the choice of concentrator geometry required is the working temperature that is desired. For low and medium temperatures ($<$350°C) the degree of concentration required is moderate. For example, if water is to be heated to 100°C only, the use of booster mirrors along with flat-plate collectors is adequate. These booster mirrors are merely plane mirrors placed at a suitable orientation with respect to the flat-plate collectors, to direct additional sunlight onto the absorber plate. Such an arrangement would have a maximum CR of 2 (if the mirror area=flat-plate absorber area), but the actual CR would be closer to 1 than to 2. The main problem with concentrators is the necessity to track the sun during its diurnal motion, and to account for the change in solar declination that occurs more slowly, with the sun having its maximum declination of $+23.5°$ on June 21 and the minimum declination of

$-23.5°$ on December 22. For the medium temperature ranges of 100 – 350°C, it is possible to think of avoiding tracking altogether by using linear (or two dimensional) concentrators that are placed along the north-south direction and tilted facing the south (in the northern hemisphere). There are a large family of such two dimensional concentrators, which include such types as

(1) tubular collectors

(2) parabolic cylinders

(3) non-imaging two dimensional concentrators, like compound parabolic devices, trapezoidal grooves, etc.

With these devices the CR can vary from 1.5 to as high as 100. With some of these no tracking is required, while with some only monthly adjustments are necessary, and some need tracking all the time. For achieving higher temperatures (500°C) three dimensional concentrators become essential. Here again non-imaging type of concentrators utilising conical elements have been proposed and tried out. Of the imaging type of collectors, the spherical and parabolic reflectors are the two possible geometries that are commonly chosen. With a spherical reflector a very special situation occurs, in that the image of the sun follows a fixed path along the line joining the center of curvature of the mirror and the center of the sun, when the reflector is held stationary. So it is possible to design a concentrator where the reflector is stationary and the absorber is tracking the sun. With parabolic reflectors nothing short of continuous tracking will work.

In the design of concentrators the major considerations are the acceptance angle, the uniformity of intensity achieved at the absorber, the minimum size of the absorber that is required, tracking requirements, etc. We will briefly examine the various types of concentrators that are commonly used.

2.4 Two Dimensional Concentrators

2.4.1 Evacuated Tube Collectors

From equation(1) it is easy to see that for getting higher temperatures both the convective and the radiation losses are to be reduced. While radiation losses can be reduced by the use of selective surfaces, convective losses can be reduced to some extent by incorporating honeycombs in the flat-plate collectors [1]. But significant reduction of convection is acheived by evacuating the air from the absorber. For this, however, the most viable geometry is the tube within which it is easy to hold a vacuum. Figs 2.8-2.11 show schematically [2,4] the cross sections of several evacuated tube type collectors. Not all of these concentrate the incoming radiation. For example, the type shown in Fig. 2.8 merely surrounds a flat absorber plate with an evacuated cylinder. In Fig. 2.9 is shown a concentric tube collector constituted only of glass or plastic, thus avoiding glass to metal seals. The third type (Fig. 2.10) uses an evacuated vacuum bottle virtually like a wide mouth

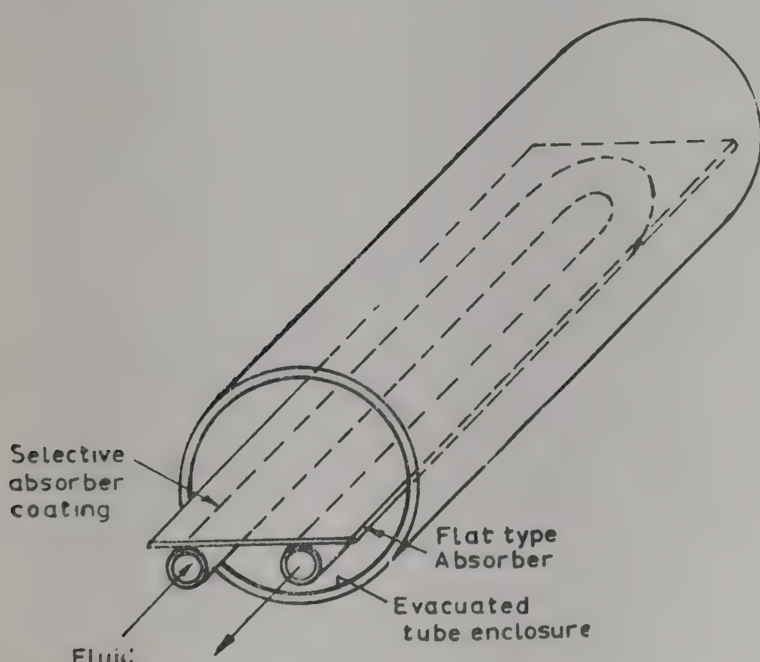


Fig. 2.8 Flat-Plate Absorber Evacuated Tube Collector

Dewar flask into which a metal absorbing cylinder, carrying the heat exchanger is introduced ; in this design too, there are no glass to metal seals. The fourth type (Fig. 2.11) is the Philips collector which is mildly concentrating (CR upto 2), and has a double U tube or a single flow through tube equipped with fins as the absorber.

These evacuated tubes are packed one next to the other and fluid flow pipes are connected up as required to form a a collector panel. Since close packing of these tubular collectors can result in shading losses at any angle other than normal incidence, usually the tubes are spaced apart and a back reflector is used to capture the radiation passing in between

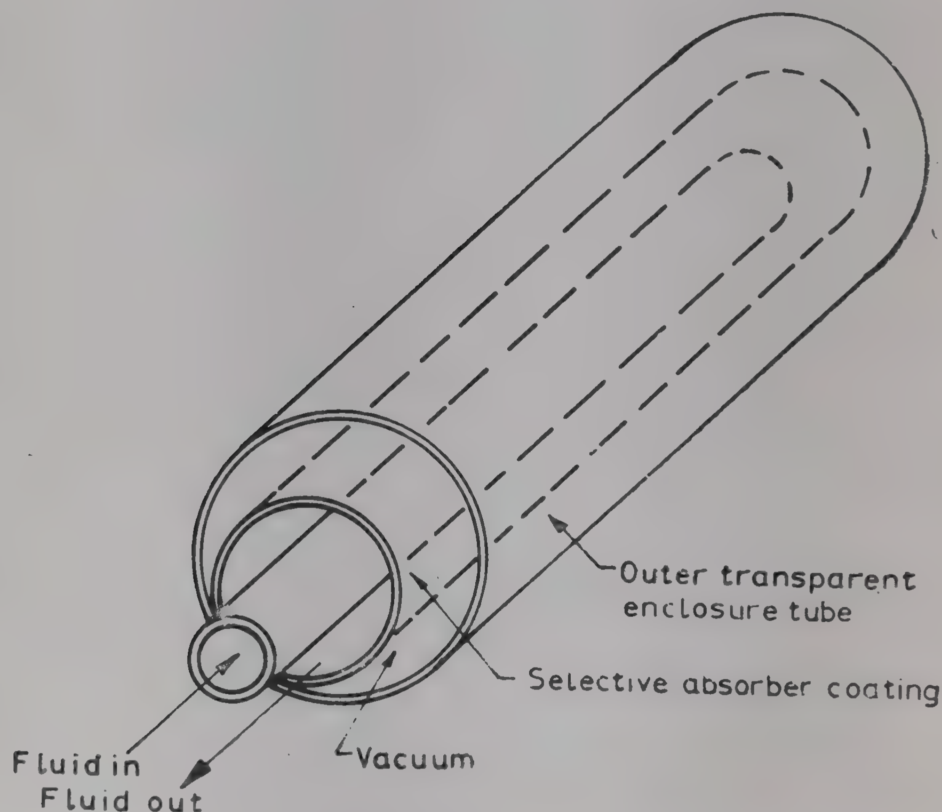


Fig. 2.9 Concentric Tube Type Evacuated Tube Collector (Does not need glass to metal seals)

the tubes, as shown in Fig. 2.12. For the absorber shown in Fig. 2.8 and 2.11, close packing can be utilised.

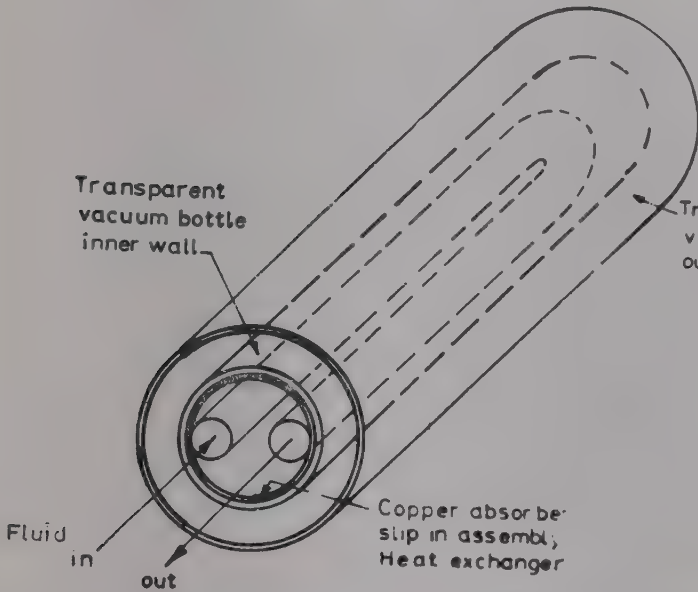


Fig. 2.10 Vacuum Bottle Type Evacuated Tube Collector

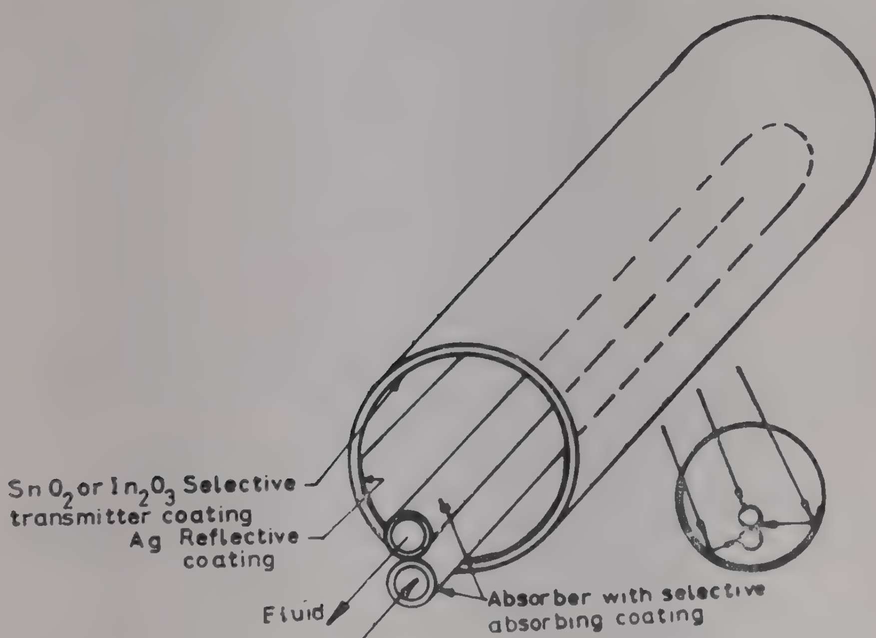


Fig. 2.11 Philips Type Evacuated Tube Collector

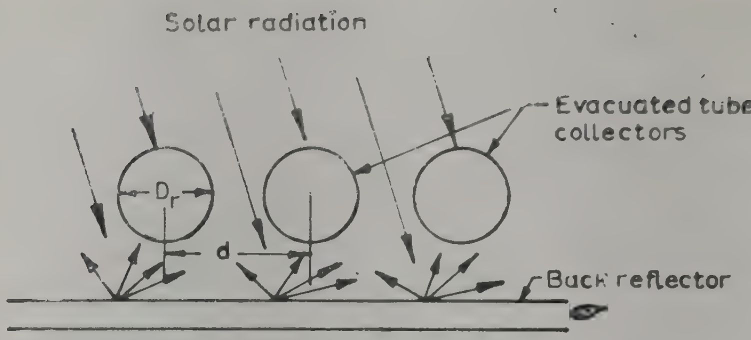


Fig. 2.12 Evacuated Tube Collector Panel with Back Reflector

The performance of the evacuated tube collectors can be evaluated along the same lines as described in the section on flat-plate collectors [1]. However, the optical analysis is a little more involved, since the reflector (see-Fig.2.12) contributes reflccted radiation to the absorber [1]. An optical efficiency can be defined as :

$$\eta_{opt} = \tau\alpha I_{eff}/(I_b + I_d) \tag{18}$$

Where I_{eff}, I_b, I_d are the total effective solar radiation intercepted by the absorber, the beam and diffuse components of solar radiation respectively. This optical efficiency is not a simple collector property but depends on the incident angles and hence varies with time for a given solar radiation.

The useful heat collected by the device is

$$q_u = I_{eff}\ (A_t/A_c) - (U_c\ T_r - T_a)\ (A_r/A_c) \tag{19}$$
$$= (D_r/d)\ [\tau\alpha\ (I_{eff} - \pi U_c\ (T_r - T_a)]$$

where A_t is the projected area of the tube, A_r is the absorber area, A_c is the collector area, D_r is the absorber diameter, d is the spacing between tubes.

The heat loss coefficient U_c can be as small as 0.5 to 1.0W/m^2°C- achieved by evacuating the enclosure and using a selective absorber coating on the absorber. The degree of vacuum required is of the order of 10^{-3} to 10^{-4} torr. Heat transfer in the annulus between the envelope tube and the absorber tube that occurs due to convection is first suppressed

on evacuation, since the Rayleigh number (the parameter that determines the onset of convection) falls below the threshold for convection to occur when the pressure is reduced. (Rayleigh number is a function of the square of the density). Heat transfer by conduction in gases is not affected by pressure as long as the mean free path is less than the gap 'g'. Once the mean free path is greater than this gap (i.e. rarefied gas regime) the heat transfer reduces drastically. The relation between heat transfer rates by conduction at normal pressures and that in vacuum is [2]:

$$q_{vac}/q_k = 1/(1+2\lambda/g) \tag{20}$$

where, λ is the mean free path ($\simeq$ 7 cm at 10^{-3} torr).

The performance of typical evacuated tube collectors is shown in Fig. 2.13.

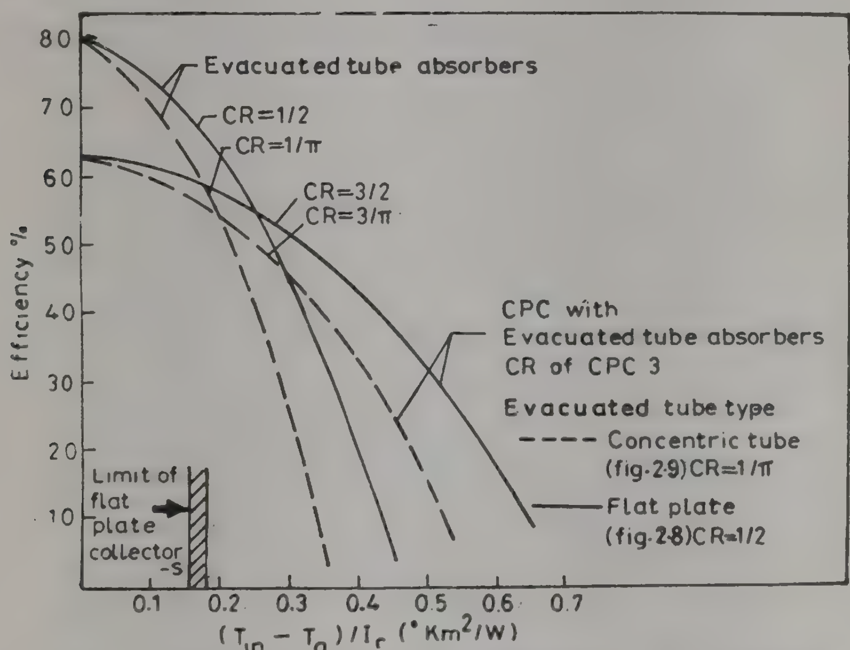


Fig. 2.13 Typical Instantaneous Efficiencies of Evacuated Tube Collectors and CPC

2.4.2 Compound Parabolic Concentrators

An ideal concentrator which achieves the highest possible concentration of solar radiation permitted by the second law of

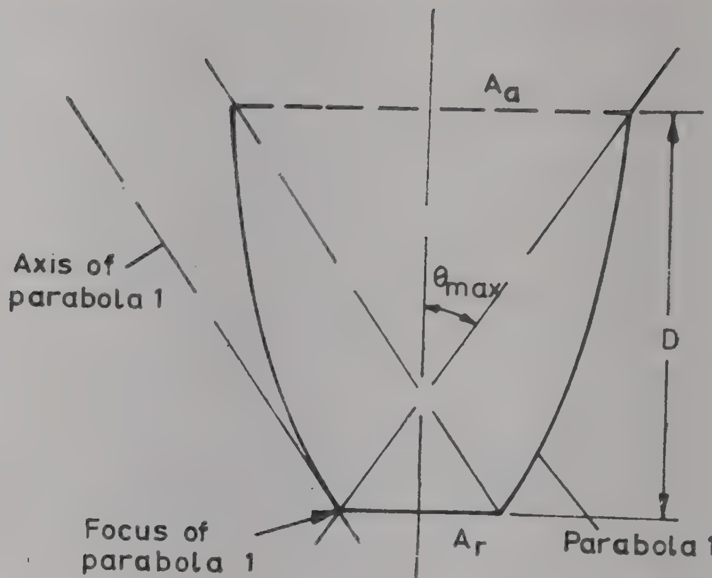


Fig. 2.14 Compound Parabolic Concentrator. An ideal Non Imaging Device. All rays with $\theta > \theta_{max}$ falling on A_a reach A_r with or without reflections

thermodynamics, is the compound parabolic concentrator (CPC) first described by Winston [5]. This CPC accepts (see Fig. 2.14) all the rays impinging on the aperture area A_a with angles of incidence $|\theta_{in}| < \theta_{max}$, and concentrate them onto the absorber of area A_r, such that

$CR = A_a/A_r = n/\text{Sin}\,\theta_{max}$, for a two dimensional geometry (and $CR = n/\sin^2\theta_{max}$, for a three dimensional geometry).

where, n is the refractive index of the medium. Such a collector does not form an image of the source, but in applications like solar energy collection since concentration rather than image formation is of importance the CPC can be used. The CPC family can achieve in practice the upper limit of the CR, whereas most other concentrators fall short of the ideal limit by factors of 2 or more. The simplest CPC is formed by two parabolic segments, the foci of which are located at the opposing receiver surface end points. The axes of the parabolic segments are inclined to the axis of CPC by θ_1, the half

angle of acceptance. The absorber is a flat surface joining the two foci. The depth D of the CPC is given by

$$D=A_r\,[(CR+1)\,(CR^2-1)^{1/2}/2] \tag{21}$$

In practice this depth D is found to be rather large and since the upper portion of the parabolic reflector does not contribute much, the CPC can be truncated by as much as 50%, without seriously affecting the performance. (The CR is reduced by about 10%). Due to imperfections in the reflector surfaces and finite size of the source (sun's disk) the actual CR achievable in a practical CPC device would be somewhat reduced. Assuming that imperfect reflector surfaces cause random errors and using angles p and q as the surface error, and solar beam displacements, their standard deviation σ_p and σ_q, are then measures of these two deviations. Then the actual CR becomes

$$CR=1/\sin\,[\theta_1+k(4\sigma_p^2+\sigma_q^2)]^{1/2} \tag{22}$$

Here k is a parameter which determines the fraction of randomly distributed rays actually captured. For $k=2$, about 95% of the rays are captured. σ_p and σ_q are typically 1/4° and thus the effect of these errors is to effectively increase the acceptance angle θ_1 by about 1/2°. Essentially then rays whose angle of incidence $|\,\theta_{in}\,| < \theta_1-k(4\sigma_p^2+\sigma_q^2)^{1/2}$, would be accepted, while rays with angles $|\,\theta_{in}\,| > \theta_1+k\,(4\,\sigma_p^2+\sigma_q^2)^{1/2}$ are rejected.

When a CPC is to be used throughout the year, tilt adjustments are necessary to locate the sun's incidence angle within the acceptance angle θ_1. Since the smallest diurnal angular excursion of the sun occurs in the north-south plane the axis of the CPC is oriented along the east-west direction and tilted (tilt angle β) for best collection. This tilt angle will have to be readjusted periodically depending on the acceptance angle. The table below shows the frequency of

readjustment required over a year. This can be computed by using the relation [6]

$$\tan(\theta_t + \beta - L) = \tan\delta / \cos(\pi n_h / 24) \qquad (23)$$

where n_h is the number of hours of collection desired.

The thermal performance analysis of these collectors is also carried out in a manner similar to that for flat-plate collectors (see chapter 3, ref. [3]). The only differences are terms corresponding to solar radiation reaching the absorber and the radiation losses from the absorber to the sky.

TABLE 2.1

Frequency of tilt adjustment for an East-West oriented concentrator to obtain a minimum of seven hours of collection per day

Acceptance half angle	Ideal Concentration Ratio (CR_{max})	Avg. Annual collection time (hr/day)	Min. No. of adjustments required per year	Shortest period without any adjustment (days)	Avg. Collection if tilt adjusted every day (hr/day)
19.5°	3.0	9.22	2	180	10.72
14°	4.13	8.76	4	35	10.04
11°	5.24	8.60	6	35	9.52
9°	6.39	8.38	10	24	9.08
8°	7.19	8.22	14	16	8.82
7°	8.21	8.04	20	13	8.54
6.5°	8.83	7.96	26	9	8.36
6°	9.57	7.78	80	1	8.18
5.5°	10.43	7.60	84	1	8.00

The useful heat collected per unit absorber area is

$$q_u = (CR.\tau(i) I_b + \tau I_d) \rho^{\bar{n}} \alpha - U_c (T_r - T_a) \qquad (24)$$

where, $\tau(i)$ is the transmittance of covers in the incident direction i, while τ is the transmittance averaged for all directions, $\bar{n}$ is the average number of reflections suffered by the

rays at the reflector before reaching the abosorber, which can range between 0.25 to about 1.25, increasing with the CR and D/A_a ratio [6], and ρ the reflectivity of absorber. The optical efficiency of the collector is

$$\eta_o = \rho^{\bar{n}} \tau \alpha \zeta \simeq (0.85)^{0.9} (0.9 \times 0.9) \times 0.95 \simeq 0.6 \text{ to } 0.7 \quad (25)$$

ζ is a parameter to take into account the beam to diffuse properties of local solar radiation;

$$\zeta = [I_b/(I_b + I_d)] + (1/CR)\,[I_d/(I_b + I_d)] \quad (26)$$

The overall efficiency,

$$\eta_c = q_u A_r / (I_b + I_d) A_a$$

$$= \rho^{\bar{n}} \tau \alpha \zeta - [U_c(T_r - T_a)]/[CR(I_b + I_d)] \quad (27)$$

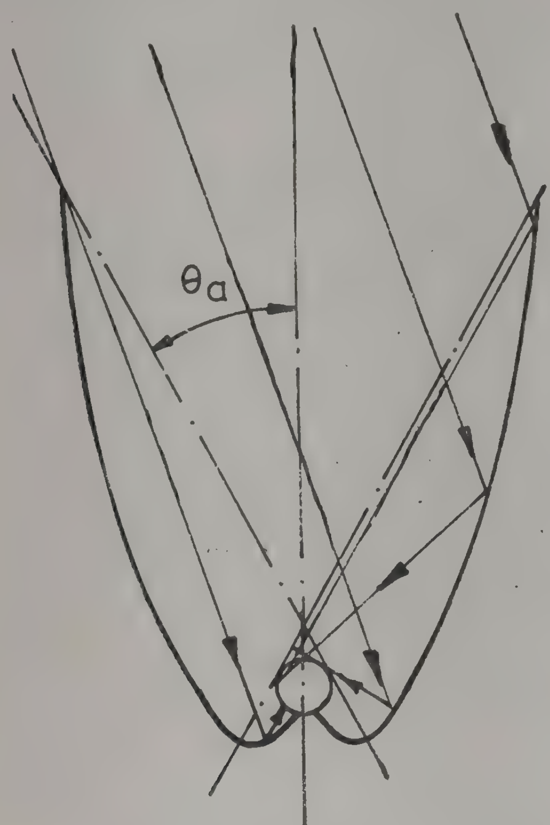


Fig. 2.15 Nonimage CPC collector with acceptance angle θ_a, Tubular receiver. Cusp Shaped reflector having parabolic sides.

Since, the optical efficiency is rather low, (i.e. the first term in the above expression), the CPC is less efficient when compared to a flat-plate collector for low values of $(T_r - T_a)/I$. But at elevated temperatures the efficiency of the CPC is higher than that for flat-plates because of the concentration and the ease with which U_c can be reduced. Furthermore, it is possible to use evacuated tube collectors as the absorber (see Fig.2.15) which will reduce losses even more. The shape of the CPC is to be modified as shown. In the basic Winston type CPC (Fig.2.14) the sides of the CPC are parabolic segments. In the modified form the sides of the reflector are extended into quasi parabolic cusps as shown in Fig.2.15. The cusp shape is a simple geometric form [7], being the locus of a string unwrapped from the tube. This modification permits a larger absorber (tube type) to be used with fairly small acceptance angles. Fig.2.13 shows the performance of such systems.

2.4.3 V-Groove Concentrators

Instead of using parabolic sections as reflectors in a CPC, plane mirrors could be used along the sides as shown in Fig. 2.16 to form V-grooves. These could be either single faceted or multi faceted. Such concentrators are not 'ideal' like the CPC where all rays inclined at angles less than θ_1 are accepted and relayed to the receiver. For the V-grooves all the rays contained within $\theta_{max} = \theta_c - 2\theta$, are accepted fully, while those between θ_{max} and θ_c are partially accepted. The angles θ_c and Φ are found roughly as indicated in the Fig. 2.16. Although they have a lower CR, the V-groove devices are much simpler to fabricate and hence hold some advantages over the CPC. For the V-groove concentrator the geometric concentration ratio [8] is

$$CR_{vg} = A/B = \sin(3\Phi + \zeta)/\sin(\Phi + \zeta) \qquad (28)$$

and $$CR_{max} = 1/\sin(\theta_{max} + \Phi) \qquad (29)$$

It can be seen that the concentration ratios for V - groove concentrators are smaller in comparison to the CPC.

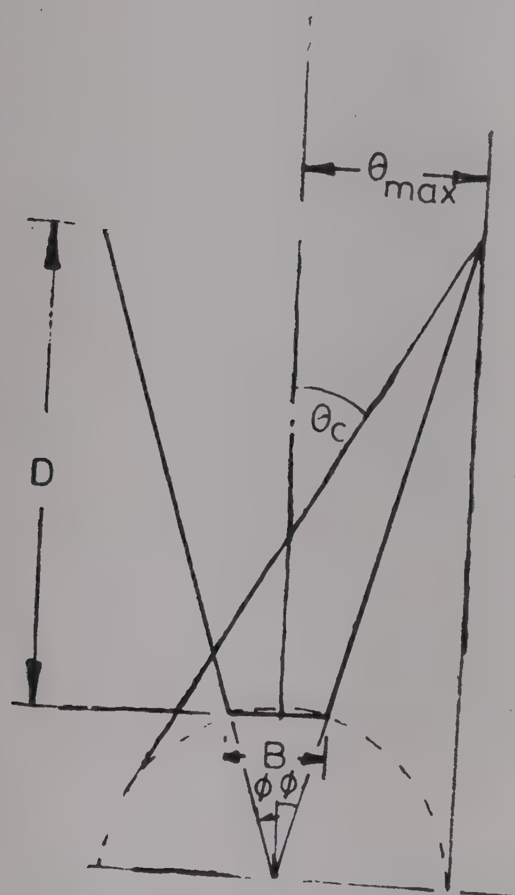


Fig. 2.16 V–Trough collector collects all rays within θ_{max} and partially rays θ_{max}, and $\theta_c = \theta_{max} + 2\Phi$, Nonimaging and Nontracking.

2.4.4 Parabolic through concentrators

It is well known that reflectors with parabolic profiles derived from conic sections like parabolic, elliptical or circular shapes produce well defined images of the light source,

Parabolic and circular reflectors are suitable for solar concentrators ; when a parallel beam of light falls on these reflectors in the direction of the optical axis, the parabolic reflector focuses the light to a point at the geometric focus, while a circular reflector focuses the parallel beam into a line along the optic axis whose length depends on the angular extent of the reflector. But if the angle of incidence of the incoming radiation is not exactly along the optic axis the image is displaced, and in the case of a parabola it is also distorted. This requires that the reflector be tracked accurately. Various other geometries have been proposed for trough like imaging collectors, besides the parabolic shape reflector. These are individually steered, curved or plane mirrors that direct the reflected radiation to a long tube held at a fixed location [2, 3] where the image of the sun is focused as the altitude angle of the sun changes during its diurnal motion. But the best known of the imaging trough like concentrators is the parabolic trough concentrator (PTC).

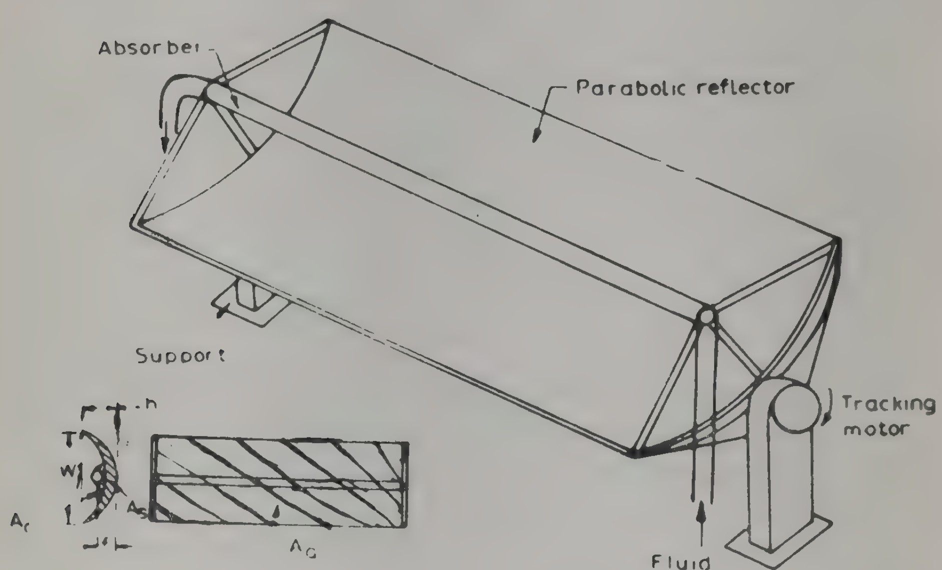


Fig. 2.17 Parabolic Trough Collector incorporating Single Axis Tracking.

Fig. 2.17 shows a simple PTC device. It consists of a reflector shaped to give the parabolic section and an absorber

(which is normally an evacuated tube collector) located at the focus. Tracking is done by rotating the mirror about its focus using a tracking device which could be a simple clockwork or a more complex unit consisting of light sensors and a feedback loop. Here again the PTC can be oriented in the east-west direction or the north-south direction, the east-west orientation shows a large hour angle effect since the angle of incidence for this orientation varies directly with the hour, whereas the north-south direction is less sensitive to the hour angle, specially if the collector is tilted up at the local latitude angle. The optical efficiency is given by

$$\eta_o \doteq \rho \tau \alpha s \zeta \, [\, (1\text{-}A \tan i) \cos i \,]\, F(\theta_t) \qquad (30)$$

where, s is the fraction of the mirror not shaded by the receiver bracket, ζ is the fraction of the reflected radiation actually intercepted by the receiver, taking into account only the imperfections of the mirror and assuming a perfect tracking, $F(\theta_t)$ is the fraction of reflected radiation intercepted by the receiver for a perfect mirror, but having an actual tracking error of θ_t in the plane of the mirror. The angle of incidence i is given by,

$$\cos i = (1 - \cos^2 \delta \, \sin^2 h)^{1/2} \qquad (31)$$

for a collector mounted in the east-west direction and continuously rotated about a horizontal east-west axis to track the sun, while

$$\cos i = (\sin L \sin \delta + \cos L \cos\delta \cos h)^2 + \cos^2 \delta \sin^2 h]^{1/2} \qquad (32)$$

for a continuously tracking collector mounted on a horizontal north-south axis. If the collector mounted on a north-south axis is now tilted up at an angle equal to the local latitude L – in the so called polar mount and then rotated, the angle of incidence depends solely on the solar declination.

$$\text{co} \;\; i = \cos \delta \qquad (33)$$

The excursion for the north-south mounting is much larger than that for east-west mounting, but it is also sensitive to hour angle variations, being totally independent in the case of polar mounting.

In the expression for optical efficiency the term Atan i takes into account the effective reduction in aperture area due to shading, blocking and loss of radiation reflected beyond the receiver tube end.

$$A = [W(f+h) + A_s - A_c]/A_a \qquad (34)$$

All the terms in the above expression are indicated in the Fig. 2.17. Typical values of A are between 0.2 and 0.3, $F(\theta_t)$ is very sensitive to errors, being 1 for zero error and reducing to 0.8 for a 1° error. Thus the overall maximum optical efficiency η_o normally lies between 60-65%. This falls off to lower values away from solar noon for an east-west mounting.

The size of the absorber depends on the size of the image of the sun at the focus. Imperfections in the surface figure of the reflectors, errors in pointing and tracking, and other imperfections lead to intensity distribution at the focus, which is approximately a normal distribution pattern. Depending upon what fraction (e.g. 90 – 95%) of this intensity falling on the focus is to be collected, the size of the absorber is fixed.

2.5 Three Dimensional Concentrators

The upper limit of concentration available with an ideal two dimensional concentrator is about 200, and to achieve a CR of about 50, with practical devices calls for very stringent limits on the accuracy of the optical surface figure and highly precise tracking. So when a CR of above 50 is required it is necessary to use three dimensional concentrators. The simplest of these are the three dimensional analogs of CPC and V-groove geometries. Such devices axicons, cones, etc., have been tried out in conjunction with solar cookers also, where the reflectors are arranged around a square or round box. When three dimen-

sional collectors are used it is essential to provide continuous tracking. The commonly used three dimensional concentrators are the spherical stationary reflector tracking absorber (SRTA), paraboloid heliostat power towers, Fresnel lenses [2, 3].

2.5.1 Spherical Reflectors

With a spherical reflector whose rim angle is small ($<$ 15°) a point focus is obtained at a distance of $R_o/2$ from the surface, when the reflector is illuminatated with a parallel

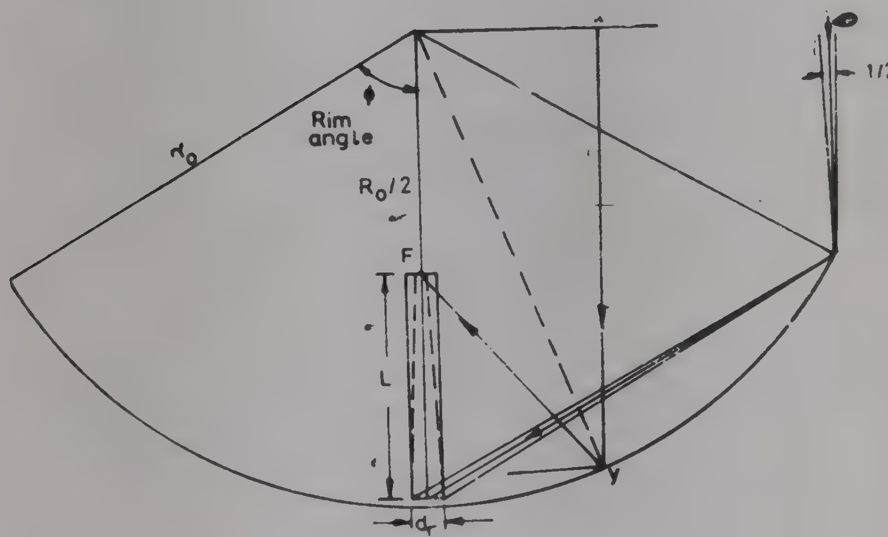


Fig. 2.18a Spherical Reflector Tracking Absosber

beam. However, when the rim angle is larger, the image llies alcng a line extending below $R_o/2$ as shown in Fig. 2.18(a) due to spherical aberration. It can be shown that the reflected rays intercept the optical axis at

$$x/R_o=(1/2)\ \{1-(r/R_o)^2\}^{-1/2}\ \{1+(D/2R_o)\ [(R_o/r)-(2r/R_o)]\}\ [35]$$

For the ray where x=0 the volume of y is $R_o/2$ (or the focus) and for the rays for which $y=R_o$, x is $0.865\ R_o$. Beyond $x>0.865R_o$, two reflections are required for the ray to reach the axis. So, if only one reflection is desired, the limiting rim

angle is 120°. The largest size of the image of the sun's disk occurs at $y = R_o/2$ and

$$d_{i,\,max} = 2\,l\,\tan 16'/3 \simeq 2l\pi/360 \tag{36}$$

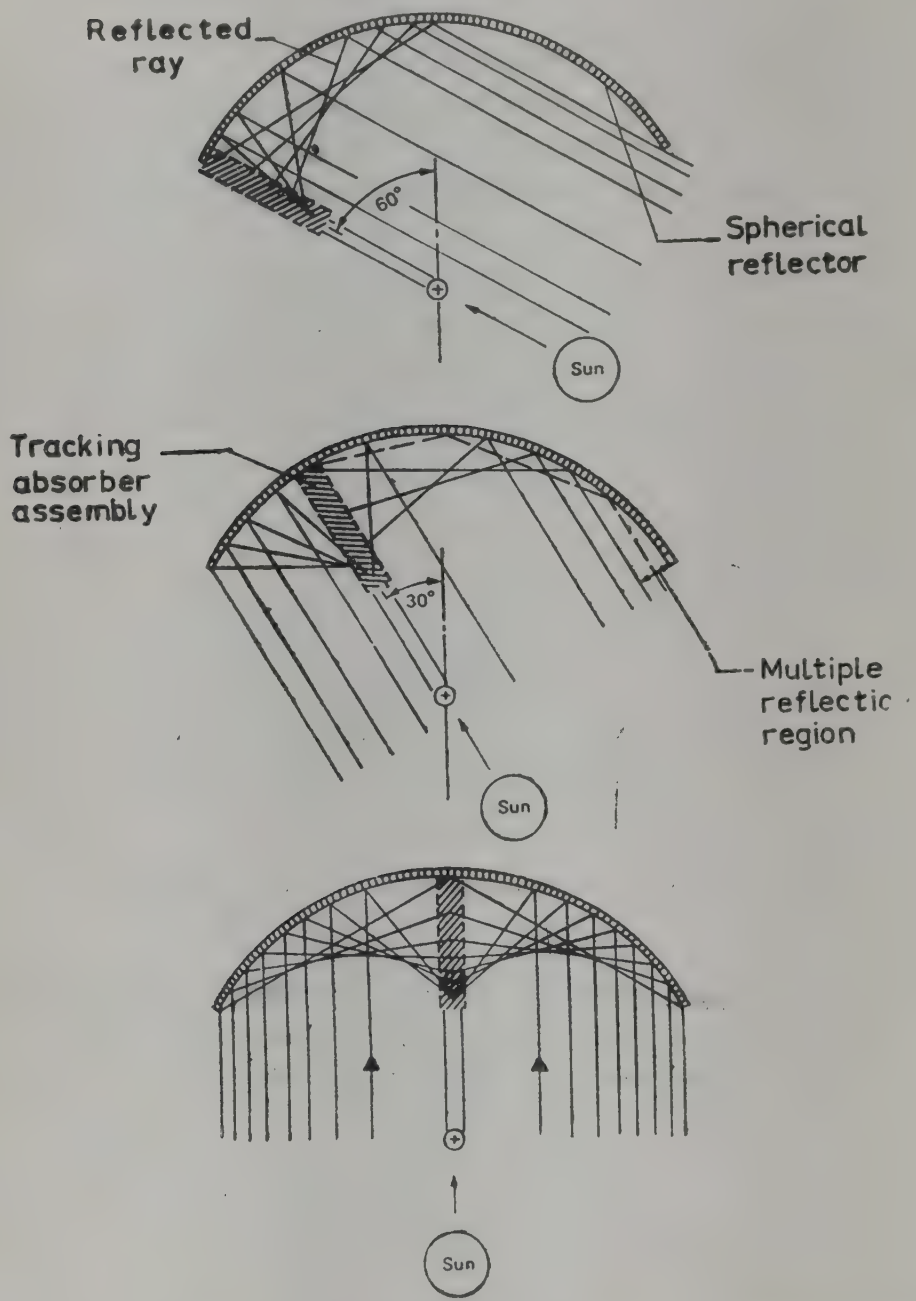


Fig. 2.18b Spherical Reflector showing positions of Absorber for 60°, 30° and 0° Incidence Angles.

Thus the diameter of the absorber D should be equal to or larger than this. The CR is then

$$CR = A_a/A_r = (R_o \sin \Phi)^2/\pi Dl \tag{37}$$

Since the absorber needs to extend from $R_o/2$ to R_o, $l = R_o/2$, thus

$$CR = 2[R_o \sin^2\Phi/D] \tag{38}$$

As before, an optical efficiency can be expressed as

$$\eta_o = \rho\tau\alpha(\text{Cos } i)\zeta, \tag{39}$$

for a reflector with perfect optics and an ideally tracked absorber, where ρ is reflectivity of the mirror, τ is the transmissivity of the receiver envelope, α is the absorptivity of the receiver, ζ is the fraction of the aperture that is not shaded and i is the solar incidence angle.

2.5.2 Parabolic Reflectors

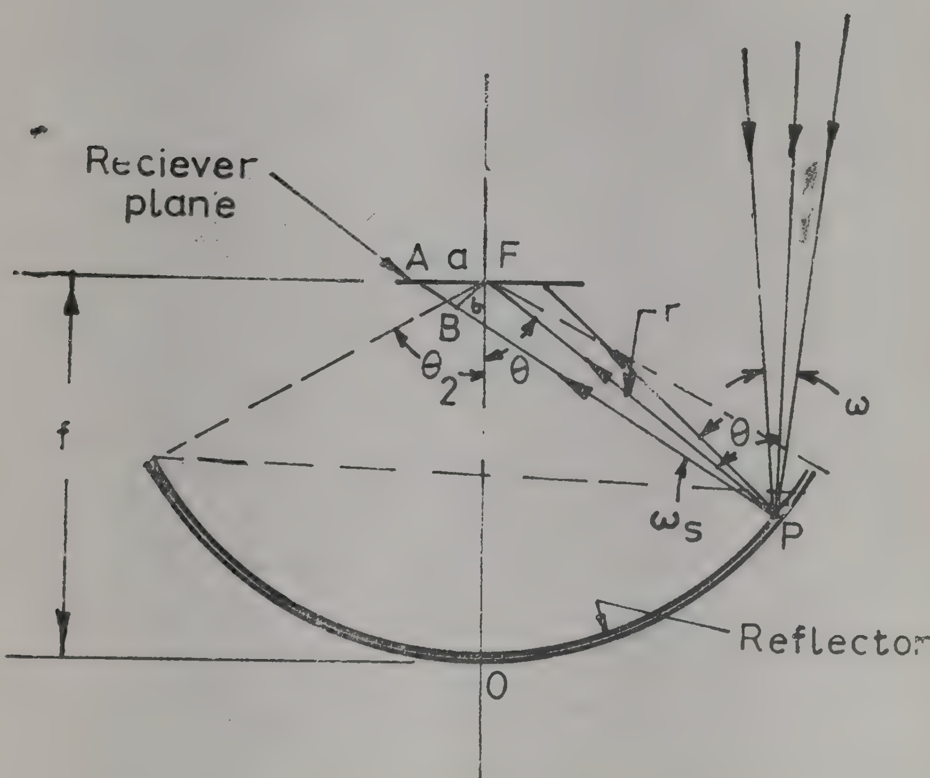


Fig. 2.19 Section through a Paraboloid Reflector

For a perfect paraboloid the sun's image depends only on the focal length and is given by

$$r = 2f/(1+\cos\theta) \tag{40}$$

where the quantities f, r, b, and θ are defined in Fig. 2.19. But the plane passing through F intersects the cone and forms an ellipse with semi-minor axis b and semi-major axis a

$$a = fw_s/[(1+\cos\theta)\ \cos\theta] \tag{41}$$

The maximum solar flux concentrated within the sun's image is

$$P_s = \pi I_s f^2\ [\sin^2\theta_2 = \sin^2\theta_1] \tag{42}$$

and the concentration efficiency can be defined as a ratio of the power received within the area of the sun's image to the total power reflected for an ideal reflector with ideal tracking

$$\eta_c = \eta_o P_s/\eta_r I_s(\pi D^2/4) \simeq \eta_o(1+\cos\delta)^2/4 \tag{43}$$

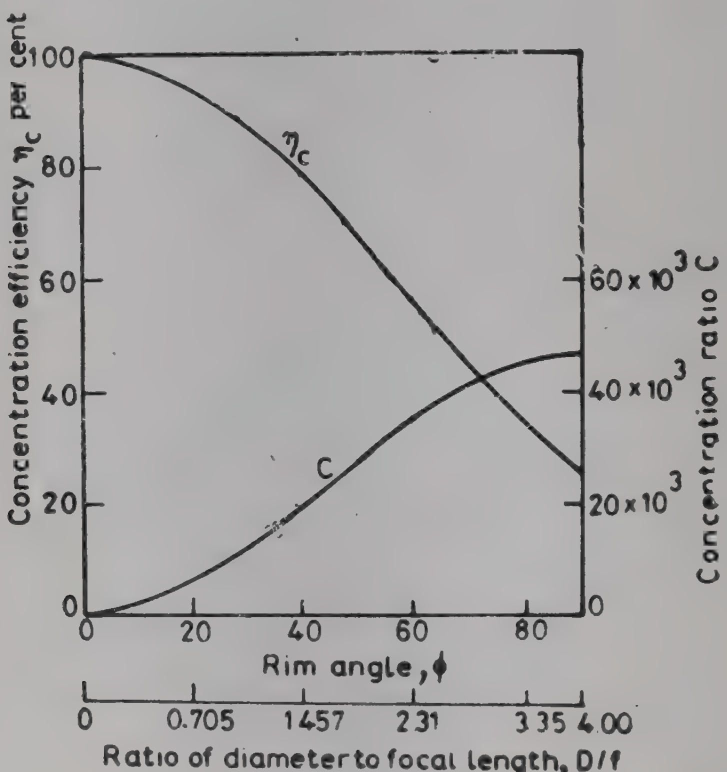


Fig. 2.20a Concentration Ratio and Ideal Optical Efficiency for a Paraboloid Concentrator.

where, the ratio D/f is 4s in $\theta_2/(1+\cos\theta_2)$. Fig. 2.20 shows the ideal collector efficiency and CR's possible for a perfect paraboloid. As with the PTC, here again the imperfections in mirror surface, errors in tracking and other errors cause a degradation in performance (η^o of the order of 0.7 to 0.8).

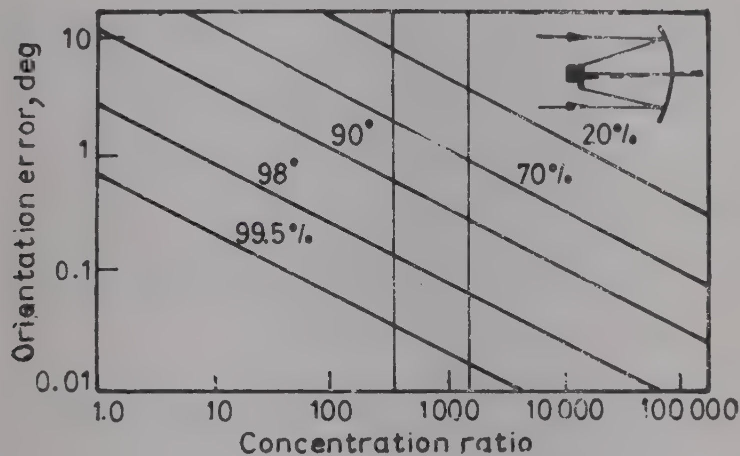


Fig. 2.20b Effect of error in pointing or tracking on efficiency for Paraboloid.

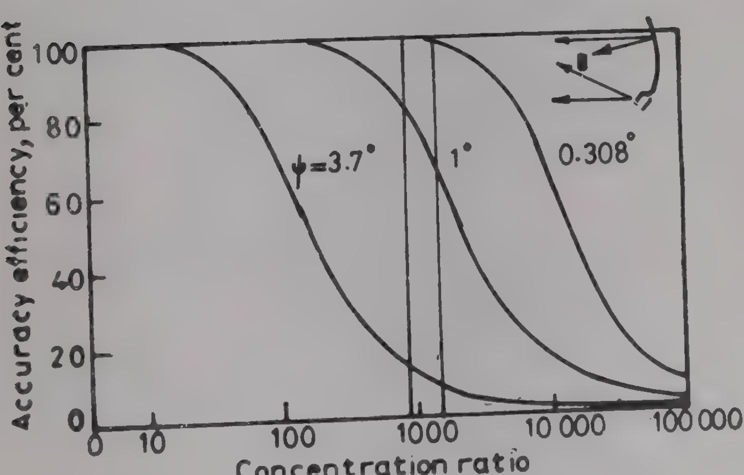


Fig. 2.20c Effect of Mirror Surface Inaccuracy Φ on the efficiency for a Paraboloid.

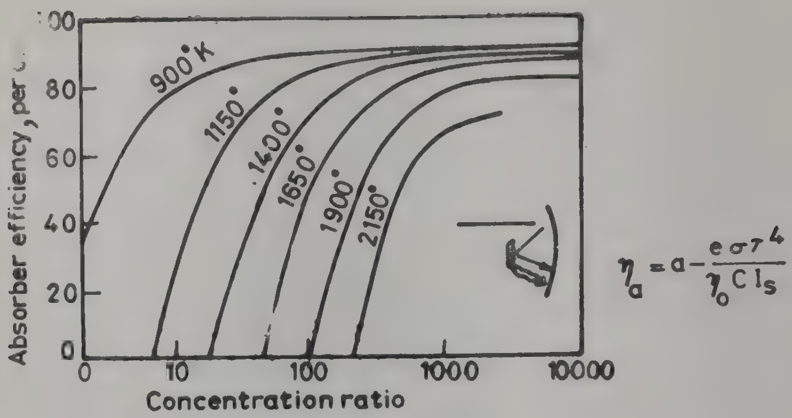


Fig. 2.20d Effect of Concentration Ratio on Absorber efficiency assuming accuracy of ±0.5. Surface accuracy of 0.3° Reflectivity of Mirror 0.9 Absorbtivity $\alpha_s = 0.9$

2.6 Power Tower

When very large energy collection is required individual concentrators become unfeasible. In such a situation a centrally situated receiver-collector receiving solar radiation relayed by a large number of mirrors located around the receiver is most suitable. Such an arrangement has several advantages, such as, avoiding complications in plumbing and carrying the hot working fluid over long distances, rotating joints etc., use of plane mirrors which are individually steered (heliostats), high CR's possible (3000 or higher). Fig. 2.21 (a to c) shows a power tower schematically.

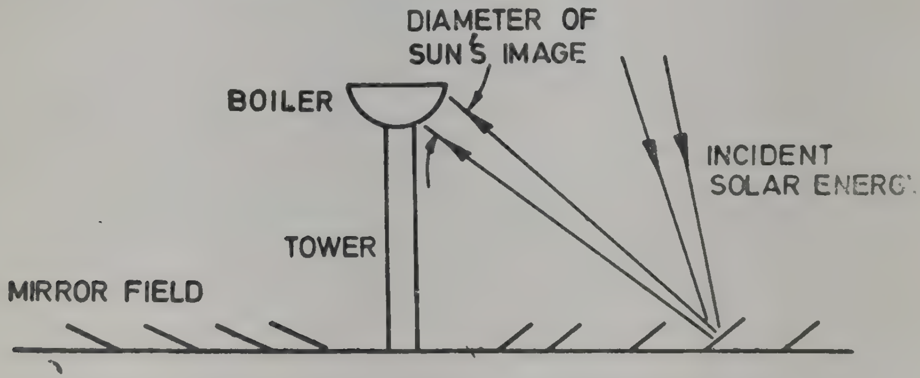


Fig. 2.21a ower Top-Focus Solar Collector

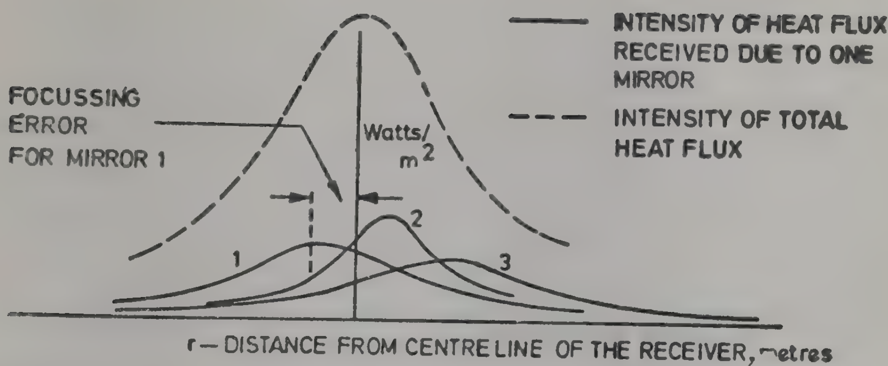


Fig. 2.21b Heat Flux Distributions

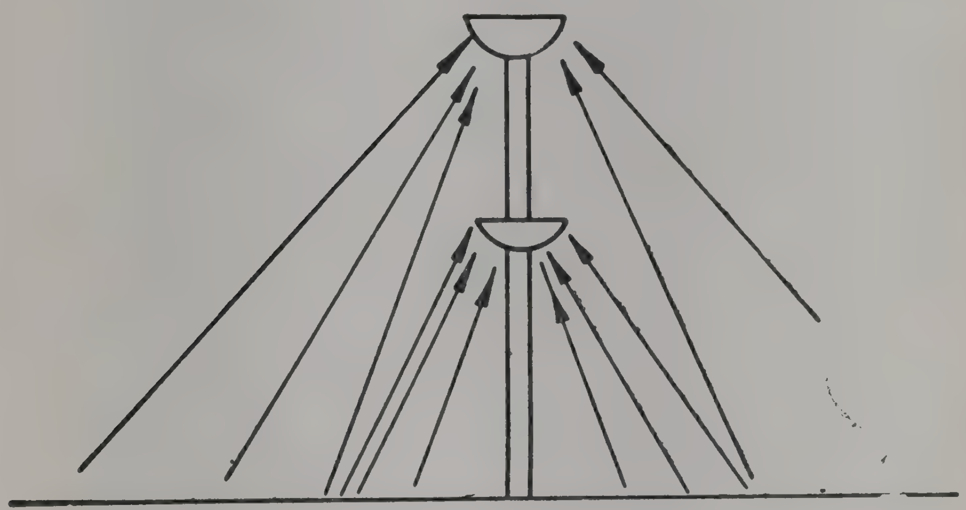


Fig. 2.21c Split-Boiler Design

2.7 Circular Fresnel Lenses

Lenses are ideally suited for concentration of solar radiation. But the cost and weight for large apertures preclude their being used. However, Fresnel lenses mitigate this advantage to a large extent. A Fresnel lens is divided into a number of zones, the spacing of which can vary between a few tenths of a mm to several cms. Within each zone the surface of the lens is tilted so that it refracts light through the same angle, as a normal spherical lens of the same focal

length (see Fig. 2.22). In general, these facets are flat, but have a tilted surface. Only if the facets were significant in relation to aperture radius, and larger than the desired focal image size, would the curvature of the facet become necessary. The equation of tilt of the facet as a fraction of the aperture zone h, and focal length F, for a material of refractive index n is:

$$\sin r_i = \sin\Phi/n, \quad \sin \alpha = n \sin (\alpha r_i), \quad \tan \alpha = h/F \tag{44}$$

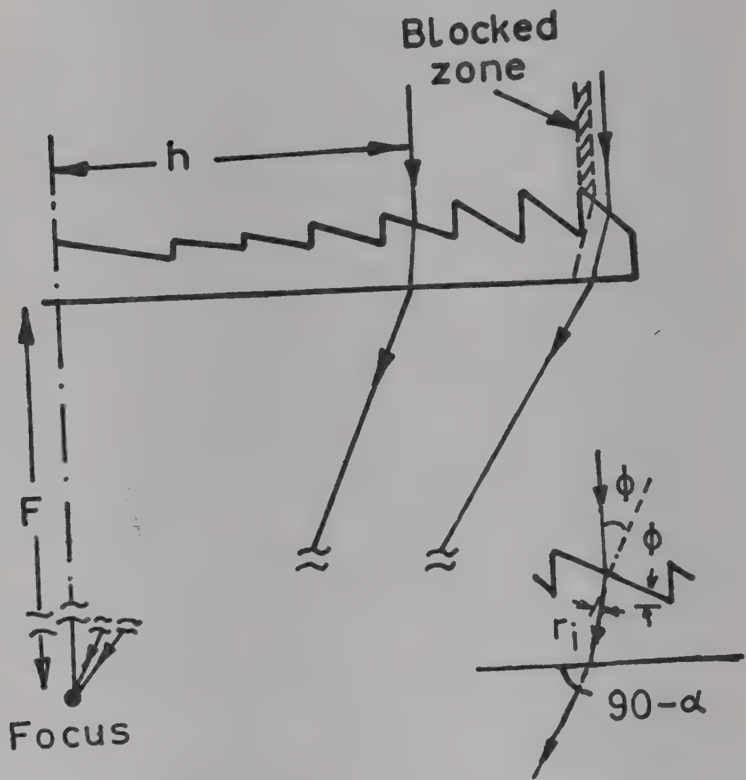


Fig. 2.22 Fresnel Lens

Plastic or glass Fresnel lenses are used in conjunction with cells in some concentrators, of a fairly small size. Such a combination considerably reduces the cost of the total device. Very high brightness concentration ratios, as high as 2000K, can be obtained with a precision plastic lens. The maximum brightness of CR, is considerably less than what is practicable with

paraboloids, because the angle of deviation by the prismatic lens element is much less than what is possible by reflection with a mirror. If, for example, the maximum inclination Φ of the outermost facet is 60°, then the maximum deviation possible is $\alpha_{max} = 42°$ for glass, whereas a full aperture angle of 180° is possible with paraboloid mirrors, as shown in Fig. 2.2.

The general performance figures of concentrator type of collectors is shown in Fig 2.4. The only major points to be gathered from this study are that: (a) depending on the highest temperature desired the type of concentrator can be chosen, (b) the degree of complexity of design, fabrication and maintenance increases with CR, (c) such a device could find rural application be it in a small foundry where metals with fairly low melting points can be melted, or in boiling water where required, using a simple concentrator, or for cooking food, (d) it may be also used to sterilize medical and surgical instruments, (e) the utility of concentrating type of collectors in rural areas is rather limited at present primarily because of its high cost and sophistication.

2.8 Development of Concentrators

As we have seen there are three classes of concentrators, those that produce no image, those that produce either a line focus or a point focus. The point focus types have circular symmetry, and are used where high concentration ratios are required like in solar furnaces and central receiver power systems. Certain other concentrators that have circular symmetry but produce a line of focus limited length - like a spherical bowl reflector or truncated cone (oxicon) have lesser concentration ratios and are generally used for solar engines or for heating. Line focus systems have cylindrical symmetry and have medium concentration ratios, while non-imaging types are also mostly linear devices and have low concentration ratios. These units are all in various stages of development as shown in Fig. 2.23. The parabolic trough concentrator is readily available from several manufacturers abroad, in Japan, Australia, USA, France etc. In India none of these are yet in common use and it is

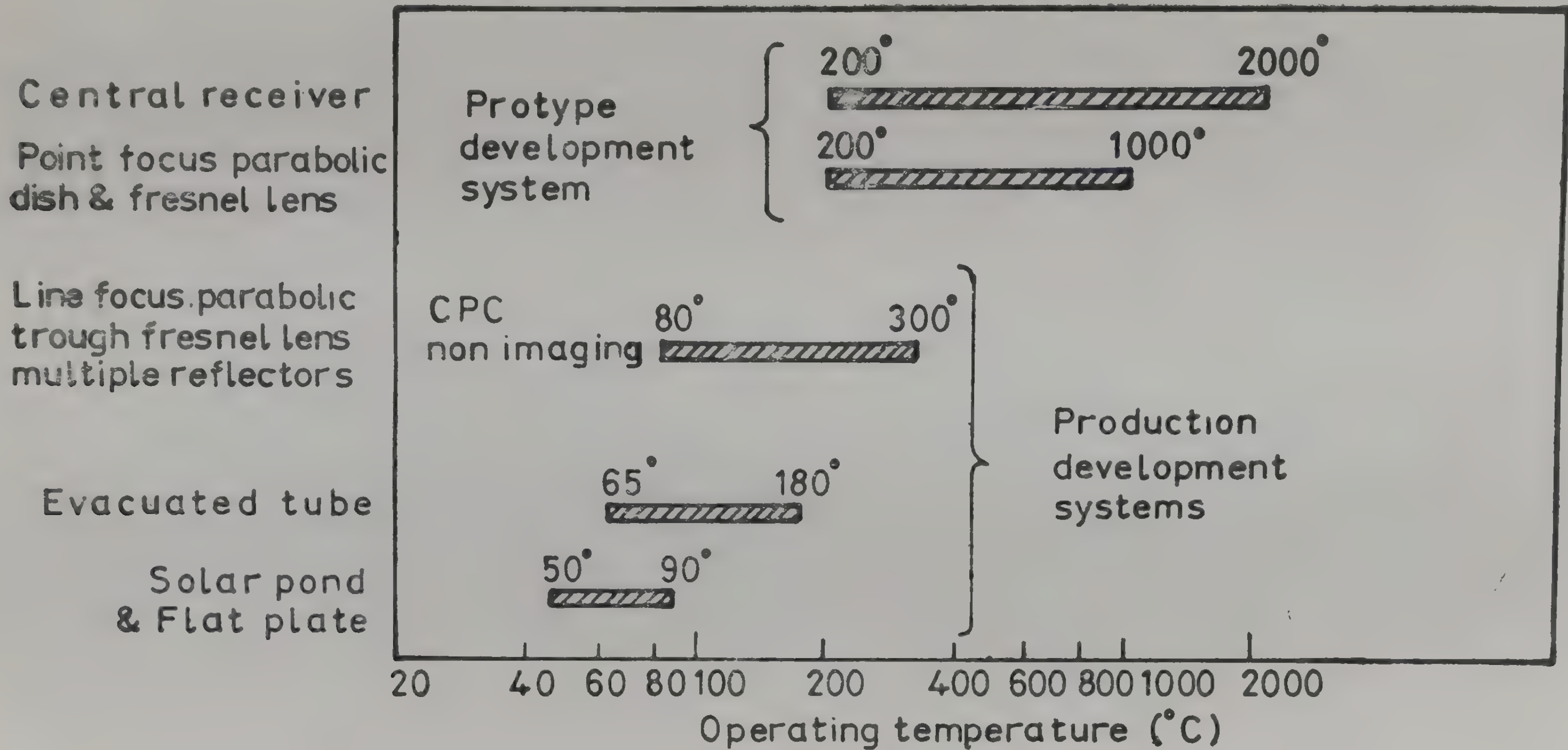


Fig. 2.23 Practical Operating Temperature Ranges of Solar Thermal Collectors.

only custom made by a few manufacturers. The tracking mounts are also not readily available off the shelf in India. It is thus safe to say that as far as concentrators are concerned the industry is still in its infancy.

2.9 Materials for Concentrators

a) **Mirrors :** The performance of a concentrator is directly affected by the optical efficiency which is directly related to the reflectivity, surface figure accuracy, etc. So the mirror has to have as high a reflectivity as possible, be easy to form to the desired shape, and retain its high reflectivity and shape even after exposure to the weather for a long period. Since, in solar applications cast is a very crucial parameter, the cost of reflectors has to be low which implies that inexpensive and light mirrors or lenses are to be considered. Glass mirrors have many good properties. They can either be silvered on the back with silver and protected to form an excellent high reflectivity, durable, second surface mirror, which however has some drawbacks, because glass that is unsupported is liable to break, and unless specially figured by grinding, does not easily conform to shapes, other than flat, by simple bending. First surface mirrors can be coated on metallic substrates. Aluminium protected with overcoating of aluminium oxide, magnesium fluoride or cerium oxide is fairly durable and has a high reflectivity, while silver is not suitable for a first surface reflector since it is easily tarnished, even when over coated, due to the diffusion of oxygen or sulphur dioxide through the overcoat. Thin aluminium sheets form very good mirror substrates. Aluminium sheets with a surface layer of electropolished, high purity aluminium and overcoated with a thin layer of oxide is available commercially in USA under the trade name of Alzak.

Aluminized plastic sheets are readily available and inexpensive. These films also have an excellent reflectivity. When Mylar films are used as a substrate, the reflector sheet will

have mechanical properties and a low thermal expansion coefficient. But these films are not very durable. Another type of plastic sheet is made by sandwiching a reflective layer of silver between two films of plastic-the bottom with Mylar and acrylic on the top. Such a sheet has good abrasion resistance, due to the acrylic, good transparency to light and good mechanical properties. The low cost of reflective plastic films makes them very attractive for use as reflectors. Flat mirrors can be formed by stretching the film over a rigid ring, but when concave mirrors are to be formed several difficulties are encountered. These concern the surface flatness of the film and sticking the film to a pre-formed substrate. Vacuum forming and pressure forming have been tried out, but are not very satisfactory. A novel idea that has been proposed, incorporates two circular plastic films, one transparent and the other reflective, fused at the rim. By applying air pressure a concave mirror is formed of approximately spherical shape [7].

A more recent innovation is to bond a very thin flexible sheet of glass, silvered on the back to a thin steel backing sheet. This composite mirror turns out to be fairly flexible and can easily be laid on a form, and by suitable clamping serve as an excellent specular reflector of parabolic or other shape. But this kind of mirror made by Carl Zeigs Jena and other companies is not availabe in India and is very expensive. Curved mirrors can also be formed by using a mosaic array of small flat mirrors laid on a backing structure which is first configured properly. Table 2.2 and 2.3 give a comparison of fixed and tracking solar concentrators, and the design parameters for solar concentrators.

(b) Structural Supports

Reflective mirrors : paraboic, cylidrical, circular, spherical or paraboloidal shapes are commonly used in concentrators. There are two appoaches used in forming these mirrors. In the first case the mirror substrate is itself shaped in the desired

Table 2.2 Comparison of Fixed and Tracking Solar Concentrators

Concentrator type	Tracking requirement	Approximate range of CR	Approximate maximum operating temperature above ambient	Acceptance angle
Compound parabolic	Fixed tilt and no tracking	1.5—2.0	Upto 100°C (Simple absorber)	At CR = 1.8 Accepts diffuse
Concentrator - CPC	—do—	—do—	Upto 140°C (evacuated tube absorber)	rad. from 68°. Good for hazy sky areas
V-Groove Concentrators	Upto two tilt adjustments per year	1.5 –2.0	Upto 140°C (evacuated tube absorber)	At CR=3, Accepts
CPC	—do—	3.0	Upto 180°C (,,)	diffuse rad. from 39° of sky
V-Groove	Seasonal and more frequent tilt adjustments	2—3	Upto 180°C (,,)	
CPC	—do—	3—10	100-150°C (Simple absorber), 150-250°C (evacuated tube)	At CR=6 accepts diffuse rad. from 20° of sky.

Concentrator type	Tracking reguirement	Approximate range or CR	Approximate minimum operating temperature above ambient	Acceptance angle
Linear Fresnel lens	Continuous tracking	6–30	150-250°C	
Parabolic trough	—do—	15—50	200-300°C	
Fresnel Mirrors	—do—	—do—	—do—	Accepts only beam radiation (1/2°).
Fixed Mirror moving absorber	Continuous tracking of absorber	20—50	300°C (upto 400°C with selective absorber, evacuation and second stage concentrator)	Usable only in clear sky areas
Spherical Reflector	Tracking absorber	50–150	300—500°C	Accepts only beam radiation (1/2°).
Fresnel lens (circular)	Continuous two axis tracking	100—1000	300—1000°C	
Power tower with field of heliostats	Continuous tracking of heliostat	1000 –3000	500—2000°C	Usable only in clear sky areas
Paraboloid dish	Continuous tracking	500—3000	500—2000°C	

Table 2.3 Design Parameters of Solar Concentrators

Collector Parameter	TWO DIMENSIONAL CONCENTRATORS Non imaging CPC	Parabolic mirror cylindrical receiver	Parabolic mirror flat receiver	THREE DIMENSIONAL CONCENTRATORS Paraboloid mirror spherical receiver	Paraboloid mirror flat receiver	Spherical mirror cylindrical receiver
CR/CR_{max} for perfect optics	1.0	$\sin^2\Phi/\pi$	$\sin\Phi\cos(\Phi+\theta_1)-\sin\theta$	$\sin^2\Phi/4$	$\sin^2\Phi\cos^2(\Phi+\theta)-\sin^2\theta$	$2\sin^2\Phi \sin\theta$
$\bar{n}$	0.7 - 1.2	1.0	1.0	1.0	1.0	1.0
ζ	$[1+\sigma_d \cot\theta]^{-1}$	**		$1-\exp(-L/\sigma_y^2)$		No simple expression
y_2	—	$\frac{A_a\sigma_d^2(2+\cos\Phi)}{12\Phi\sin\Phi}$	*	$\frac{2A_a\sigma_d^2(2+\cos\Phi)}{3\Phi\sin\Phi}$	$\frac{2A_a\sigma_d^2}{\sin^2\Phi}$	—
L	D/2	D/2	D/2	$\pi D^2/4$	$\pi D^2/4$	D/2
A_a	Aperture width	Aperture width	Aperture width	Area of Aperture	Area of Aperture	Area of Aperture

Φ=Mirror rim half angle

θ=Acceptance half angle

L=Characteristic dimension of receiver

D=Receiver width or diameter

σ_d^2=Sum of squares of standard deviations of mirror surface error (σ_p^2) and solar beam displacements (σ_q^2)

σ_y^2=Standard deviation of flux pattern at the focus of collector

$\bar{n}$=Average number of reflections of ray before reaching focus

ζ=Optical capture factor

$$* = \frac{A_a^2(4\sigma_p^2+\sigma_q^2)}{4\Phi \tan^2(\Phi/2)}\left[\frac{2}{(3\sin^3\Phi)} - \frac{1}{3\sin^3\Phi\cos\Phi} + \frac{2}{\sin\Phi} - \frac{\cos\Phi}{3\sin\Phi} - \frac{2\Phi}{\sin\Phi} + \frac{4\sin\Phi}{3\cos\Phi} - \ln\tan\left(\frac{\pi}{4}+\frac{\Phi}{2}\right) + \ln\tan\left(\frac{\pi}{4}-\frac{\Phi}{2}\right)\right]^{1/2}$$

$$** = (2\pi\sigma_y)^{-1}\int_{-L/2}^{-L/2} \exp\left[-0.5(y/\sigma_y)^2\, dy\right.$$

configuration. In the second case a thin reflective film is laid on top of the desired configuration. Usually a light skeleton frame made from steel or aluminium is built first and the reflector is then attached to the frame. To keep the weight of the assembly low the reflector is made out of light or rigid reinforced plastics, etc. Since, most communication equipment use large parabolic dish type antennas, it is possible to adopt these antennae for making parabolic dish type solar absorbers, by laying an optical reflective film on top of the dish. Such a dish has been fabricated in the Department of Mechanical Engineering, Indian Institute of Science, Bangalore, for melting metals [8].

(c) Tracking

As has been already described, depending upon the type of concentrator, the tracking unit will have to perform either north-south or east-west diurnal tracking on one axis for line focus devices, or on two axes for point focus collectors. For following the sun three methods are commonly used-the time system, the servo system or the manual system. The time system is conveniently set up by the equitorial mounting; by having an axis parallel to the earth's axis about which the concentrator is rotated at a constant speed so as to diurnally follow the sun. Seasonal changes are affected by adjusting the tilt of the concentrator. Another possible tracking mounting is the azimuth mount, where the elevation and the azimuth of the concentrator mirror are made to be the solar altitude α and the azimuth a.

In the servo system, photovoltaic detectors are used to determine whether the mirror is exactly normal to the solar beam or not. If the mirror is not normal to the solar beam an error signal is generated which is then utilised to drive the azimuth and altitude motors, to bring the mirror to an exactly orthogonal relation with the solar beam. The manually tracking devices are most commonly used in solar cookers or furn-

Table 2.4 Tracking and Solar Incidence Angles

Orientation of collector	Incident factor cos i
1. Fixed horizontal plane surface	$\sin L \sin \delta + \cos L \cos \delta \cos h$
2. Fixed plane surface tilted such that it is normal to solar beam at equinoxes, at noon	$\cos \delta \cos h$
3. Rotation of plane surface about a horizontal east-west axis with a single daily adjustment for the surface normal to coincide with solar beam at noon, every day	$\sin^2 \delta + \cos^2 \delta \cos h$
4. Rotation of plane surface about horizontal east-west axis continuously for maximum energy incidence	$(1 - \cos^2 \delta \sin^2 h)^{1/2}$
5. Rotation of plane surface about horizontal north-south axis continuously for maximum energy incidence	$[(\sin L \sin \delta + \cos L \cos \delta \cos h)^2 + \cos^2 \delta \sin^2 h]^{1/2}$
6. Rotation of plane surface about an axis parallel to earth's axis continuously for maximum energy incidence	$\cos \delta$
7. Rotation about two perpendicular axes continuously to keep the surface normal coincident with solar beam at all times	1

aces where by actually seeing the image of the sun, the orientation of the mirror is centered on the receiver (see Table 2.4).

2.10 Problems, Prospects and Tasks

The cost of the concentrator collector is currently much higher than that of the flat-plate collector, when viewed from either the aperture area basis or from an energy collection basis. This is primarily because the development of concentrators is still far from being complete. Development and further research work on various aspects of all the component parts of the concentrators is worthwhile and can be undertaken. Some of these problems are listed below (this list is not comprehensive).

2.10.1 Reflector : Different geometries have been proposed for the reflector, but both analysis and fabrication can be undertaken. For example, the use of V-groove reflectors in troughs, or use of simpler geometries formed by a cantilever shape, for non-imaging troughs, in addition to parabolic or truncated parabolic sides; use of cones with single or multiple cone angles (axicons), inverted prismatic shapes (inverted pyramids), spherical, parabolic or other shapes formed by making air or water filled pillows, refracting devices using water filled plastic lenses for line and point focus systems, Fresnel reflectors and lenses are some of these.

Both substrate and reflective films can be studied for use as reflective materials. The use of honeycomb substrates, FRP substrates, moulding of complex geometries with FRP, provision of vacuum or pressure forming of plastic reflective films, preparation of metal sheets-electropolishing, anodizing etc., use of segmented mirrors are a few of the studies that can be carried out.

2.10.2 Receivers : Receivers capable of operating at medium and high temperatures (100-500°C) can be studied both analytically and experimentally. Receivers enclosed in transparent

tabular encloures with varied geometries, studies on heat transfer, energy extraction from these devices, flexible couplings for these receivers, materials, coatings, fluids for use, are all some of the aspects meriting study.

Besides these, there other aspects, viz., tracking, enclosing the concentrators to prevent deterioration of reflectors, dust proofing, cleaning, that are also important, may be examined.

In all these studies the impact of these on the overall economics of the concentrator and its application, is to be examined carefully.

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3. Solar Cookers

3.1 Introduction

The cooking of food using solar energy is a very attractive prospect; especially in our country where sunshine is plentiful for most of the year, and the cost of conventional cooking fuels like firewood, cowdung, LPG, kerosene, etc., is high, and their availability is subject to several vagaries. The prospects are even more attractive in the rural areas where nearly 80% of our population resides. It is estimated that as much as 90 to 95% of the energy consumed in rural areas goes primarily towards cooking. The fuel used for cooking is a mix of non-commerical fuels like firewood, cowdung cakes, agricultural wastes, etc. These fuels are then burnt in crude chulas where the efficiency is much lower than 10%. The severe shortage of firewood, and the serious ecological consequences of deforestation resulting from the felling of trees demands a new technology for cooking. An efficient solar cooker relying on solar energy would indeed be extremely welcome.

The cooking of food primarily involves heating a mixture of water and cereals, pulses or vegetables, to nearly the boiling temperature of water; and allowing it to simmer at that temperature for some period of time depending on the material being cooked. Following this, seasoning is carried out. In addition to boiling, other kinds of cooking operations involve frying, baking, grilling, basting etc. These methods have evolved around the use of open fires or concentrated heat sources and ovens, and they have been perfected over centuries; without much regard for the conservation of fuel. To gain wide acceptance, solar cookers must be able to carry out these tasks without drastically altering the cooking practice. However, the fact that solar energy is only available during fixed hours, and is very dilute (less than 1 kW/m^2) compared to conventional

stoves (more than 20 kW/m^2), poses very severe restraints in cooking. It is possible to develop newer methods of cooking tailored to the sun's energy density and position in the sky. However, this is likely to evolve over a long time scale and its acceptability will also be slow. It is easy to see that for solarcookers to succeed in the immediate present they have to be able to carry out the tasks of boiling, baking, etc., nearly as well as the conventional heat sources.

Solar cookers presently available fall into two broad categories the box type cooker which is essentially a flat-plate type of device, and solar ovens which employ some kind of concentrator, either the imaging or non-imaging type. We will examine these two types of cookers in some detail.

3.2 Box Type Solar Cooker

The most commonly used solar cooker is the box type of cooker. It consists of a shallow insulated rectangular box which is blackened on its inside and has a transparent glass cover at the top. The food to be cooked is kept in closed vessels inside this box. Since there is no useful heat removed from the box, all the solar energy absorbed by the black coating goes towards heating the wall and contents of the box. The maximum temperature attained depends on the heat loss suffered by this unit. At this temperature, the heat losses exactly balance the solar energy input. This is the so called stagnation temperature of the system. With a little care it is possible to attain stagnation temperatures in the range of 120 to 150°C around 11 to 1 p.m., on clear days, for most of the year. Such a box type cooker can be used for the boiling of rice, pulses, vegetables, meat, etc. and it should even be possible to carry out the baking of biscuits.

3.2.1 Analysis of Box Type Cookers

Consider a simple flat black horizontal surface exposed to the sun and covered by a transparent glass sheet, we can write the energy balance as :

$$\tau\alpha A_c I_s = q_{lc} + q_u + q_s \quad (1)$$

where, the left hand side is the energy input term, and on the right hand side the first term q_{lc} is the heat loss from the black surface to the surroundings by conduction, convection and radiation, q_u is the useful heat extracted from the surface-for example, water or air being heated in a flat-plate collector, and q_s is the internal energy stored in the system.

(a) **Stagnation temperature :**

In a cooker, since, q_u is zero the expression can be recast as :

$$\tau\alpha A_c I_s = q_{lc} + mC_p[d(T_s - T_o)/dt] \quad (2)$$

where, the internal energy stored has been written explicitly. T_o is the initial temperature. When steady state is reached, i. e. there is no change in temperature with time, or no further storage, the heat losses become exactly equal to the energy input. This condition is the ''stagnation temperature'' of the system. Then,

$$\tau\alpha A_c I_s = (q_{lc})_{stag} \quad (3)$$

For the purpose of this analysis we can examine the heat loss factor for a simple box type cooker, whose cross section is shown in Fig. 3.1 and the thermal circuit is shown in Fig. 3.2.

$$q_{lc} = U_c A_c \ (T_b - T_a) \quad (4)$$

where, the loss factor U_c is the sum of the loss from the top and bottom, and it is given by (see Fig. 3.1)

$$U_c = U_T + U_B$$
$$= 1/(R_1 + R_2 + R_3) + 1/(R_4 + R_5) \quad (5)$$

The determination of the loss factors has been considered in great detail in an earlier issue [1]. Fig. 3.3 illustrates the stagnation temperatures that can be attained if steady sunshine I_s is incident on the box. The temperatures attainable are merely representative of the values that can be practically attained, because of the non-steady nature of sunshine and imperfections in the system.

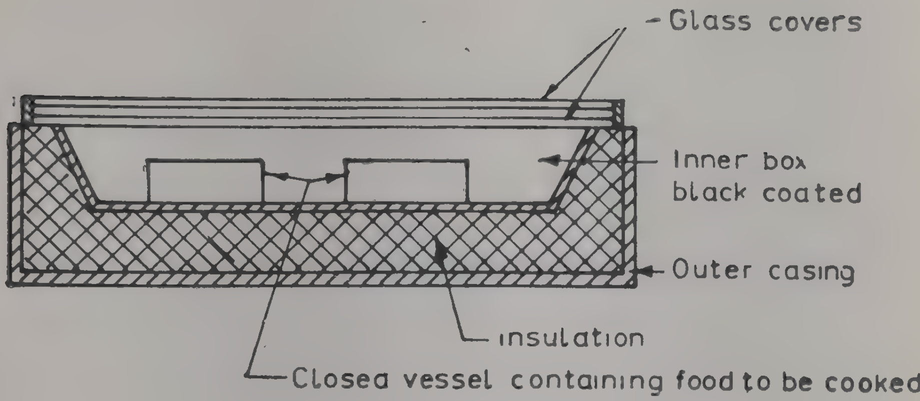

Fig. 3.1 Cross section through a Box Type Cooker

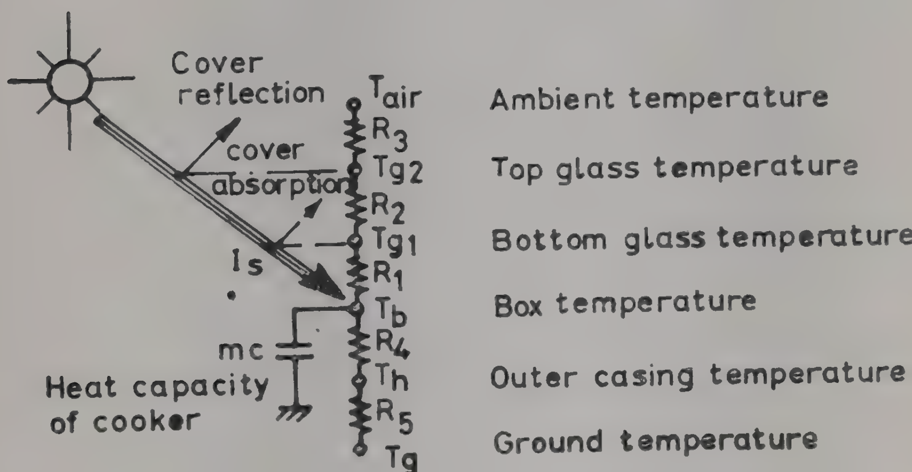

Fig. 3.2 Thermal Circuit for the Cooker

(b) Time taken for cooking:

Depending on the mass of the food to be cooked, the time taken to raise its temperature to the peak value can be estimated.

$$mc_p d\,(T - T_a)/dt = \tau\alpha A_c I_s - U_c A_c\,(T - T_a) \tag{6}$$

It is assumed that the food was initially at the ambient temperature T_a. This equation on integration yields the temperature variation with time.

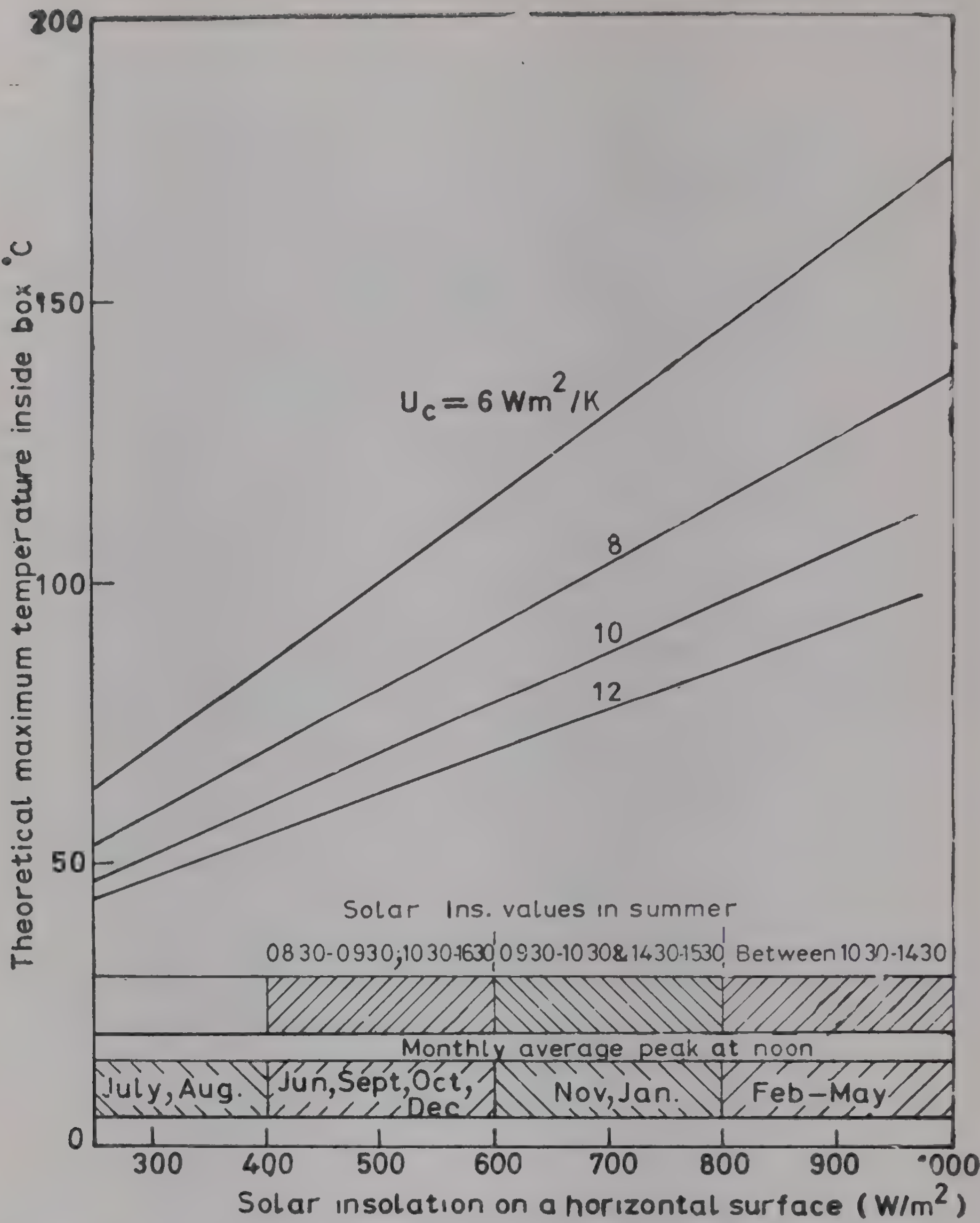

Fig. 3.3 Ideal Stagnation Temperature reached in a Box Type Cooker. (Ranges of solar insolation available during summer at different times of day are indicated in the upper boxes and peak values for different months in lower box)

By substituting the functional dependence of I_s, the solar insolation, as a function of time, the manner in which the temperature in the cooker increases can be found. Fig. 3.4 shows the variation of the cooker temperature as a function of time, on a clear day. Depending on when the cooker is placed in the sun, the time taken to reach the stagnation temperature will vary. The best time for cooking is thus between 11 a.m.

and 1 p.m. although any period between 9 a.m. and 3 p.m. can be utilised. After the temperature reaches the boiling point of water, a certain simmering period is required for completion of cooking. During this simmering period it is necessary to supply additional heat.

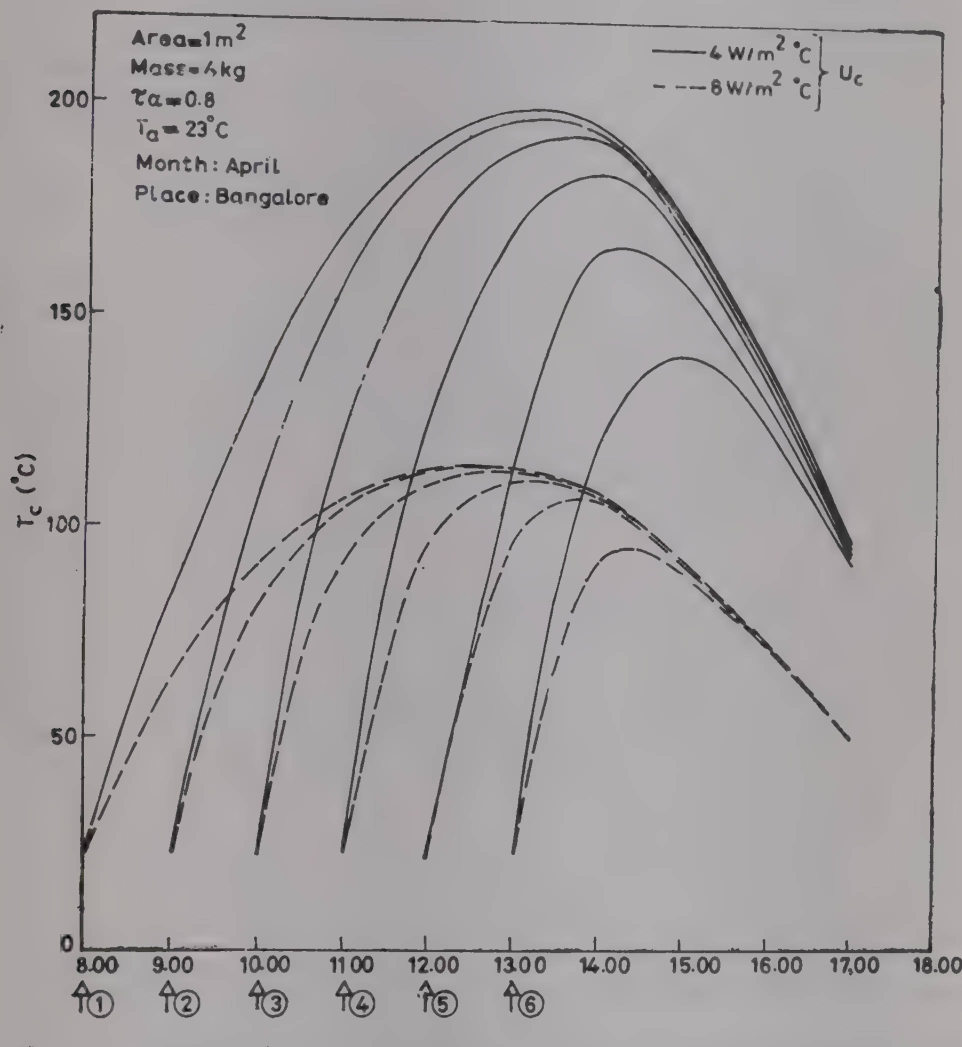

Fig. 3.4 Curves (1) to (6) indicate temperature rise in cooker when cooking cycle is started at (1)=08 00 hrs. (2)=09 00 hrs. (3)=10 00 hrs. etc. (Temperature rise calculated using only sensible enthalpies; latent heat of evaporation ignored)

This additional heat is for supplying the heat of vaporisation of water that may evaporate during simmering, and also to supply the heat of cooking. The heat of cooking refers to the energy required to initiate the chemical changes that occur when a food is cooked. It may be necessary to break down some bonds and form new chemical substances. Thus the heat of cooking is a quantity that depends on the nature of food that is being prepared.

$$q_A = m_2 L + m_3 R \tag{7}$$

where, m_2 is the mass of water evaporated, L is the latent heat of evaporation at temperature T, R is the heat of cooking, m_3 is the mass of raw food stuff being cooked (this excludes the mass of water added separately for cooking). If the cooking vessels are perfectly sealed, and no vents are provided, the temperature inside can exceed the boiling point of water at atmospheric pressure (i.e. 100° C), since, the pressure inside will exceed atmospheric pressure.

Hence, in arriving at the time required for cooking it is necessary to carry out actual experiments wherein different types of food are cooked. This can then be analysed to provide the necessary date for estimating the time needed for cooking. Some simple empirical relations have been developed by some investigators [1] which assist in getting an estimate of the time required. These empirical relations are described in a later section.

3.3 Estimating Cooking Requirements

Many paramenters influence the ease with which cooking can be carried out. These are (a) the season (i.e.,I_s) (b) the time at which the food is put into the cooker (c) the type of food being cooked - whether it is soft or hard (d) the quantity of food being cooked, i.e., the depth food in the vessel (e) size of the solar cooker (f) the type of cooker being used. Parikh [2] has evolved a very simple empirical method for approximately estimating the cooking requirements. Table 3.1 below classifies the four parameters - season, time at which cooking is commenced, nature of food and depth of food - as having different degrees of difficulty. By multplying the degrees of difficulty for the four parameters, a cooking factor or index is derived. For example, if a hard food like dal of 4cm depth is to be cooked at 10 a.m. in summer, the cooking factor would be :

cooking factor = multipliers for (summer × time of day × food type × depth) $= 1.2.3.2 = 12$

Table 3.1

Sl.No.	Factors affecting cooking time	Conditions		
1.	Season	Summer Mar–May	Moderate Oct-Nov	Winter Dec-Jan
2.	Time when food is to be cooked	1100-1300H	1000-1100 or 1300-1400H	2H after sunrise, 2H after sunset
3.	Type of food	soft	medium	hard
4.	Depth of food layer	2cm	4cm	6cm
5.	Degree of difficulty multiplier	1	2	3

The cooking factor has been again roughly correlated with the time required for cooking as shown in table 3.2 [2].

Table 3.2

Cooking Factor	Time required for cooking (hrs)
1-2	1.1
3-4	1.5
6-9	2.0
12-18	3.0
24-36	4.0
54-81	Food cannot be cooked

The variery of foods that can be prepared on a solar cooker include cereals, pulses, vegetables, roots, eggs, soups, porridges, bread, cake milk preparations, roast vegeatbles, meats, etc. Foods difficult to cook like pulses can be cooked by soaking them in water earlier. As little water as is absolutely necessary need be utilised. Those foods that need deep frying or special methods of cooking like chappaties, cannot be prepared in solar cookers.

3.4 Construction of Cookers

Just as concentrators are used for obtaining higher temperatures, even with cookers it is possible to use concentrator type collectors if temperatures exceeding 100-120°C are required: flat-plate collectors (i.e. box type cookers) can be used for temperatures under 120°C.

3.4.1 Box type cookers

As already describcd above, the simple box type cooker shown in Fig. 3.1, consists of an insulated container painted black provided with two layers of glass. This double glazing is essential since higher peak temperatures can be attained, whereas with single glazing the peak temperatures are much lower (see Fig. 3.3). In using the results of Fig. 3.3, it should be noted that these numbers are only roughly indicative, since the computations are made assuming solar insolation to be constant throughout the cooking period; whereas the radiation on a flat-plate is a function of time, being maximum at noon and reaching zero at sunrise and sunset. The results shown in Fig. 3.4 take this into account. The importance of reducing the heat losses is dramatically brought out in both these figures. Measures, such as use of selective coatings on the absorber plate, heat mirror coatings on glazing, which were mentioned in the article on solar flat-plate collectors [1] apply equally well here. But since the cost of the cooker is a very important criterion, the improvements achieved by their inclusion should be balanced against the increases in the cost of the cooker.

A plane mirror booster that is incorporated as a hinged lid (see Fig. 3.5) helps to improve the performance by mildly increasing the concentration of the captured radiation. The addition of this reflector increases the solar radiation directed at the absorber plate for most of the time, provided the cooker and the reflector are properly positioned.

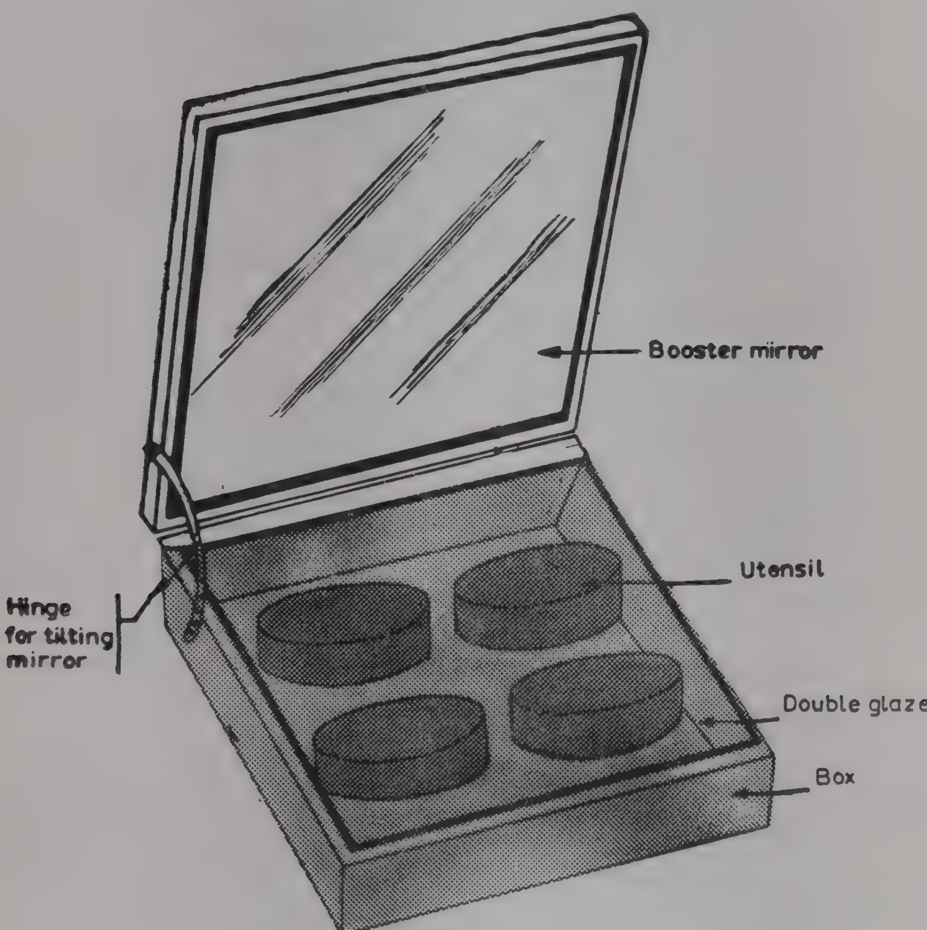

Fig. 3.5 Box Type Cooker with Booster Mirror

Various materials have been used for making these cookers. The most commonly used materials for the inner and outer boxes are mild steel or galvanized iron sheets, the inner

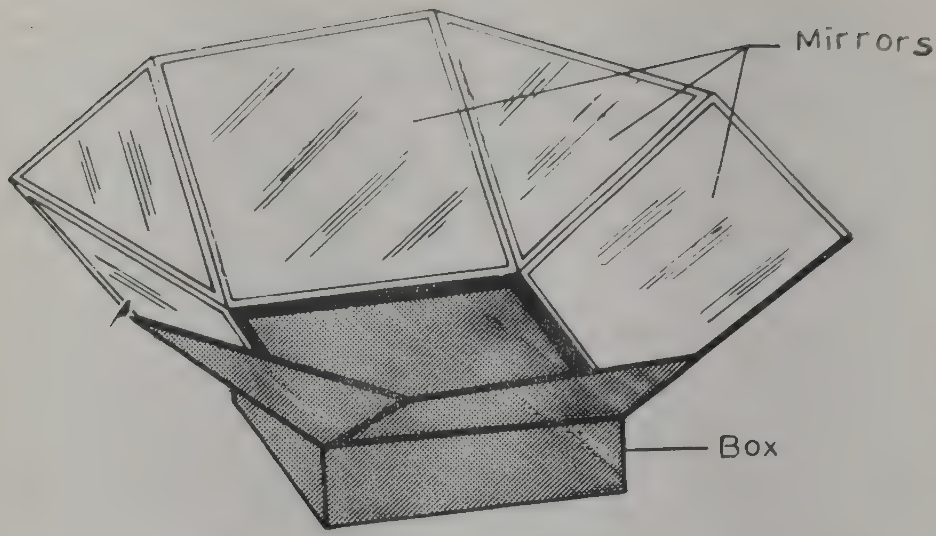

Fig. 3.6 Box Type Cooker with Concentrator using 8 Mirrors

boxes being painted black with either boiler paint or enamel or black board paint. The box is provided with a hinged lid also made of steel. The materials used for insulation are mineral wool, glass wool, paddy husk, saw dust, coir etc. Wooden outer boxes with a steel inner sheet have also been tried.

3.4.2 Concentrator type Cookers

For getting higher temperatures inside the cooker than those attainable in the box type cooker (see Fig. 3.1), and to reduce the time needed for cooking, concentrator type of collectors can be utilised. The simplest of these would involve the provision of a flat reflector (booster mirror) which can be hinged to the box and also serve as a lid. However, such a reflector can only give a very moderate concentration ratio (in the region of 1.2 to 1.5) and can provide an increase in temperature from 15 to 20°C. Fig. 3.6 shows an arrangement where 8 flat reflectors are placed around the rim of the box to

form a conical reflector. Such a device serves as a concentrator, having concentration ratios of the order of 3 to 6. The cone angle can be varied from 30 to 60°. As with any concentrator, the collector has to be oriented so as to face the sun, which requires that the unit be provided with a tilting mechanism.

Many variations of this basic type of concentrator have been tried. These variations have been: (i) use of a two step compound cone, which can reduce the need for continuous tracking, instead the concentrator position can be altered every 15 minutes or once an hour, higher concentration ratios are possible with lower acceptance angle; (ii) use of aluminized polyester sheets for reflectors. For even higher concentration ratios imaging type reflectors may be used. Parabolic dish collectors have been tried as concentrators and the sun's radiation is focused onto a small focal region where the blackened vessel containing the food to be cooked is kept. Very high temperatures are attained with parabolic concentrators. It is easy to obtain 400-500°C in the focal region for much of the day, but in order that the oven work accurately and efficiently, the reflector must be pointed towards the sun, the reflector should be accurately formed to provide a parabolic section and the reflector should have a high specific reflectivity.

One novel type of the parabolic type cooker/oven is the "Sun Basket" introduced by ICRISAT, Hyderabad. The sun basket consists of a bamboo basket frame over which papier-mache about 1 cm thick, is lined such that the interior is smooth and assumes a parabolic shape. Now, a reflector foil - either aluminium foil, aluminized polyester or silver paper is glued to the parabolic surface to form the reflector. A cooking pot with a rounded base, painted black is placed in the focal region where food is cooked in a short period, of the order of 10 minutes to half an hour. Such cookers are inexpensive (Rs. 50 to 100), but rather flimsy. The reflectors deteriorate rapidly and cannot be left in the open to the rain. Spilling of food on the

reflector surface should be avoided and continuous tracking of the sun is essential. The sun-basket can operate only on sunny days, from 8 a.m. to 4 p.m. A tracking device consisting of a counterweight that descends gradually when water in a container is allowed to leak at a controlled rate, has been used in conjunction with the sun basket and this turns out to be a very simple and effective way of orienting the cooker.

3.5 Materials for Cookers

As already seen, various materials have been utilised in the construction of the already mentioned designs. But a careful study of the functional requirements reveals that only two of the components are critical in the construction of the box type cooker. These are the inner box and the glazing. It is clear that the heat radiation absorbed by inner box walls has to be transfered effectively to the cooking vessels kept on the surface. This heat transfer is effected by conduction and by convection of the enclosed air. Aluminium would thus be the preferred material for the box walls because of its high conductivity and relatively low cost, when compared to copper. Galvanized iron or cold rolled M.S. Sheets which are commonly used for the box have a much lower conductivity and hence would take longer for cooking. In equation (6) this aspect of heat transfer has not been included, since it has been assumed that the heat conductivity of all the components is infinitely large. In an actual cooker the temperatures of the inner box walls, cooking vessels and the food inside will not be the same, as has been assumed in equation (6), to simplify matters. It is however, possible to carry out a more comprehensive analysis where the non-uniformity of temperature can also be included. The natural convective flow which can aid in heat transfer within the box is to be encouraged in the case of cookers, when contrasted to the case of flat-plate collectors where the spacing (gap) between the absorber plate and glazing is so arranged, so as to avoid natural convective

flow. A brief description of the heat transfer by convection in this enclosure was given in an earlier issue [1].

Next in order of importance is the glazing material. Here again the considerations applicable to the flat-plate absorber [1] are found to be equally valid for the cooker. The purpose of glazing is to reduce the upward heat loss, while at the same time permitting a maximum of solar radiation to be transmitted through it. Since in a cooker, as high a stagnation temperature is desirable, plastic films which soften at around 100-200°C are clearly unsuitable, this leaves only Teflon and Tedlar as possible plastic glazing materials. Use of double glazing is also a must, since with a single glazing the top losses will be fairly substantial and the peak temperatures reached will not be adequate (see Fig. 3.1). This leads to the use of double glazing (commonly low iron glass). The two sheets of glass are to be sealed together with a gasket, this glass sandwhich is then kept on the inner box, and a good gasket seal is provided. In most cookers the access to the working space is through the top, hence, glass sheets are made to be removable or hinged to be inner box. A good air tight seal is required for achieving high temperatures.

Obviously the bottom loss also has to be small. This is achieved by good insulation. The choice of insulation and its thickness can be arrived at along the same lines as described in ref [1] for flat-plate collectors.

Some cookers are placed in a pit dug in the earth, into which a metal box is embedded and then covered with a glass plate. Such a cooker will no doubt be very cheap, but will have a poorer performance, i.e. the cooking time will be much longer.

Reflectors made of glass, aluminium, aluminized polyester film are commonly utilized for concentrating sun light. Evidently glass reflectors though fragile and expensive will be the ones that serve the longest, due to their ability to maintain a high reflectivity for long periods, whereas polished aluminium

sheets lose their reflectivity rapidly in the open and are more easily scratched. Aluminium polyester film is the cheapest, very light and easy to use as a reflector material, but its life is short.

3.6 Problems, Prospects and Tasks

3.6.1. As with most solar devices, the initial cost of the solar cooker is very high in contrast to the conventional cookers, such as the simple chula or even kerosene stoves; primarily because of the large size of the solar cooker and the requirements of glazing and insulation. Thus a systematic attempt at cutting down the cost by using cheaper materials is called for, while keeping in mind that any consequent deterioration in the performance of the cooker should not render the cooker useless (i.e., the stagnation temperatures should reach 100°C).

3.6.2. Another major constraint with solar cookers is its acceptability to housewives, who in most cases carry out cooking. The need to keep the cooker in the open, and to cook between 10 a.m. and 2 p.m., rather than at other hours are the constraints that are endemic to solar cookers, although if a concentration type cooker is used it should be possible to extend the duration from 8 a.m. to 4 p.m. The possibility of using high technology solutions like employing heat pipes to convey heat collected at a remote location to the kitchen, and the storage of solar radiation either in a thermal, chemical, or electrical storage should be investigated. These solutions are bound to be expensive and would be of a limited application.

3.6.3. There are not many studies devoted to the actual task of cooking itself. Classification of food that is easy to cook or easy to adopt to solar cooking and the detailed methodology of cooking with solar cookers have to be evolved for bringing about a solar cooking culture, rather than attempting a forceful transplantation of solar cookers into the current practice of cooking. For this studies are essential. It is possible to use solar cookers as an adjunct to conventional cookers by carrying

ont some preliminary steps on the solar cookers, and then completing the rest using conventional stoves.

A more detailed theory of cooking and a more detailed estimate of economic benefits is also desirable. Exhaustive testing of many types of cookers under controlled conditions is another aspect to be studied.

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4. Solar ponds

4.1 Introduction

A solar pond is large body of water used to absorb and store solar energy. In a salinity-gradient solar pond a density gradient is deliberately introduced to inhibit the mixing of the hot fluid at the bottom and the cold fluid at the top. The density at the bottom of the pond is increased by dissolving large quantities of salt. The density of the saline water at the bottom of the pond is usually around 1.2 grams per cubic centimetre. The water at the surface of the pond is maintained almost free of salt by surface flushing. Solar ponds have the following advantages over the conventional flat-plate collectors:

1. Solar ponds can be constructed at one third to one tenth the cost of conventional flat-plate collectors,
2. Solar ponds have a built-in storage facility and hence overcome the problem of intermittent solar radiation,
3. Solar ponds are ideally suited for large scale applications since they involve much less plumbing than conventional flat-plate collectors.

4.2 Structure of the pond

The solar pond has three distinct layers as shown in Fig. 4.1. Surface winds primarily account for the upper mixed layers. The wind induced mixing maintains the temperature and salinity constant within this layer. The depth of the upper mixed layer depends upon the magnitude of the wind and can be as high as 50 cm, when the winds are very high. Heavy rain can also increase the thickness of the upper mixed layer. The lower mixed layer at the bottom of the pond is a

region where salinity and temperature do not vary with height. Solar energy is absorbed at the bottom of the pond and the heat is transferred to the lower mixed layer by convection. The thickness of the lower mixed layer is chosen depending upon the amount of energy storage required. The upper mixed layer and the lower mixed layer are separated by the non-convective zone. Temperature and salinity increase with depth in the non-convective zone. The non-convective zone permits most of the solar radiation in the visible region to reach the lower mixed layer, but inhibits the transfer of heat from the lower to the upper mixed layer (except by conduction). The thickness of the non-convective layer is usually around 1m. The thermal resistance offered by one meter of water (in the non-convective zone) is equivalent to six centimeters of Styrofoam insulation. The non-convective layer in the solar pond thus acts as a partially transparent window of low thermal conductivity that allows most of the solar radiation in the visible to pass through and heat the lower convective layer. The thickness of the non-convective layer and the clarity of the upper mixed and non-convective layers influence the efficiency of collection of solar energy in the pond.

Solar ponds are filled in layered sections with small differences in salinity between adjacent layers; such that high density saline layers are filled first, and lighter layers successively floated upon the lower denser layers. Alternatively, a concentrated solution can be made at the bottom of the pond and then a series of layers of decreasing salinity can be produced by a series of fresh water injections at successively higher levels in the solution. In order to prevent mixing of different layers the velocity of water injected should not exceed 10 cm/s. After filling the pond, the stabilizing salt concentration gradient is maintained by controlling the salt concentration in the upper and lower mixed layers.

The solar pond will be statically stable if the density increases with depth. The requirements for dynamic stability

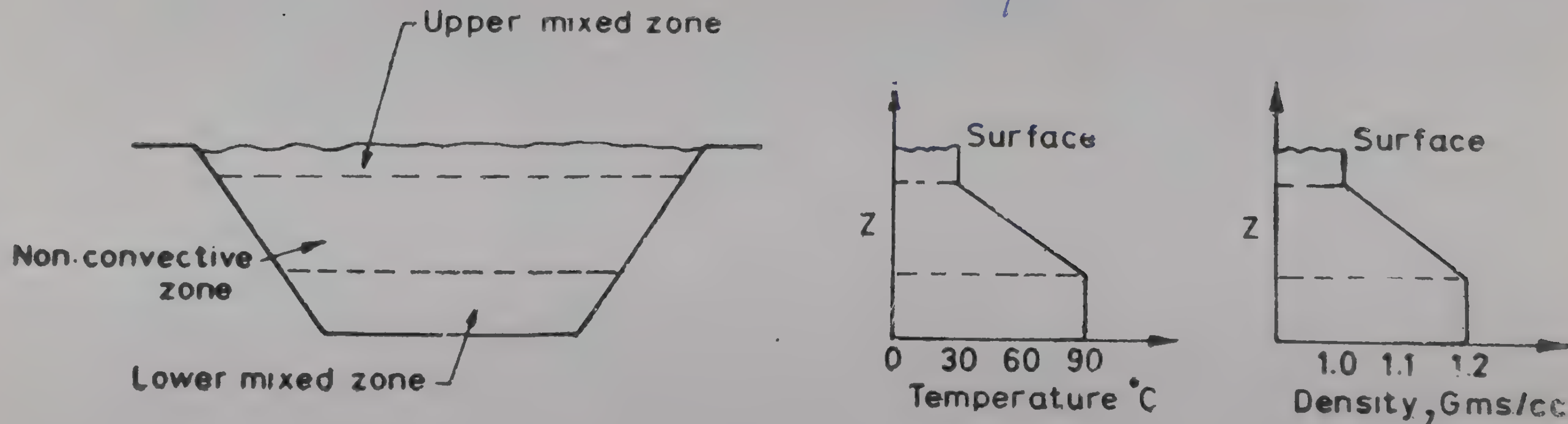

Fig. 4.1 Different zones in a solar pond

are more stringent. The solar pond will be stable if the salt concentration gradient satisfied the following requirement (small perturbations may be allowed for) :

$$\frac{\delta S}{\delta Z} > \frac{(\nu+\alpha)}{(\nu+D)} \frac{\delta \rho}{\delta T} \frac{\delta T}{\delta Z} \Big/ \left(\frac{\delta \rho}{\delta S}\right) \tag{1}$$

where, s is the salt concentration in kg/cubic meter, z is the distance from the pond surface, ν is the kinematic viscosity, α is the thermal diffusivity, D is the salt diffusivity, ρ is the density of saline water, T is the temperature.

For dilute solutions, $\nu \backsim 7\,\alpha \backsim 10^3 D$, and hence the above stability criterion simplifies to

$$\frac{\delta S}{\delta Z} > (1.14)\ \frac{\delta \rho}{\delta T} \frac{\delta T}{\delta Z} \Big/ \left(\frac{\delta \rho}{\delta S}\right) \tag{2}$$

For a solar pond using sodium chloride the value of $\delta\rho/\delta T$ is -0.3 at the pond surface, and -0.51 at the pond bottom. The value of $\delta\rho/\delta S$ is $+0.8$ at the pond surface and $+0.52$ at the bottom of the pond. The stability criterion for a solar pond using sodium chloride is therefore,

$$\delta S/\delta Z > (0.44)\ \delta T/\delta Z, \text{ for the pond surface}$$
$$\delta S/\delta Z > (1.18)\ \delta T/\delta Z, \text{ for the pond bottom} \tag{3}$$

The temperature gradients at the surface of the pond can be as high as 500°C/m. Hence, the salt concentration gradient required near the top of the non-convective layer is 220 kg/m^4. The temperature gradient near the bottom of the non-convective layer can be 200°C/m. Hence, the salt concentration gradient required near the bottom of the non-convective layer is 236 kg/m^4. A salt concentration of 250 kg/m^3 in the lower mixed layer and 10 kg/m^3 in the upper mixed layer will result in a mean salt concentration gradient of 240 kg/m^4, if the non-convective layer is one meter thick.

4.3 Heat Transfer in Solar Ponds

Depending upon the angle of incidence, about 3 to 10% of the solar radiation incident on the surface of the pond is reflected back. Most of the solar radiation in the infra-red is absorbed in the upper mixed layer. The transmissivity of solar radiation in the visible region depends upon the clarity of the pond water. If we assume that the clarity of the water in the pond is the same as that of sea water, the transmissivity $\tau(z)$ is given by

$$\tau(z) = 0.36 - 0.08 \ln(z) \qquad (4)$$

Using the above expression for transmissivity, we can show that the optical efficiency of the pond, that is the percentage of incident solar radiation that is absorbed in the lower mixed layer, is given by [see Kooi (1979) for derivation]

$$\eta_o = 0.44 - .08(z_2 \ln z_2 - z_1 \ln z_1)/(z_2 - z_1) \qquad (5)$$

where z_1 is the depth of the top of the non-convective layer and z_2 is the depth of the bottom of the non-convective layer.

The pond will attain a steady state after a long period of operation if the rate of heat extraction is exactly equal to the rate of heat gain in the pond. If the ground thermal conductivity is not large we can neglect the heat loss through the soil at the bottom of the pond. If the pond size is greater than one hectare we can neglect the side losses. The only heat loss from the lower mixed zone will be that through the non-convective layer. The heat loss coefficient of the non-convective layer is the ratio of the thermal conductivity of water (in that layer) to the thickness of the non-convective layer. If we assume the thermal conductivity of water to be 0.6 W/mK and the thickness of the non-convective layer to be 0.6 centimeter then the heat loss coefficient becomes 1 W/m^{2}K.

The overall efficiency of the solar pond operating in the steady state can now be written as

$$\eta = \eta_o - K[T_p - T_a]/[z_2 - z_1] \qquad (6)$$

where T_p is the temperature in the lower mixed layer, T_a is the ambient temperature, K is the thermal conductivity of water.

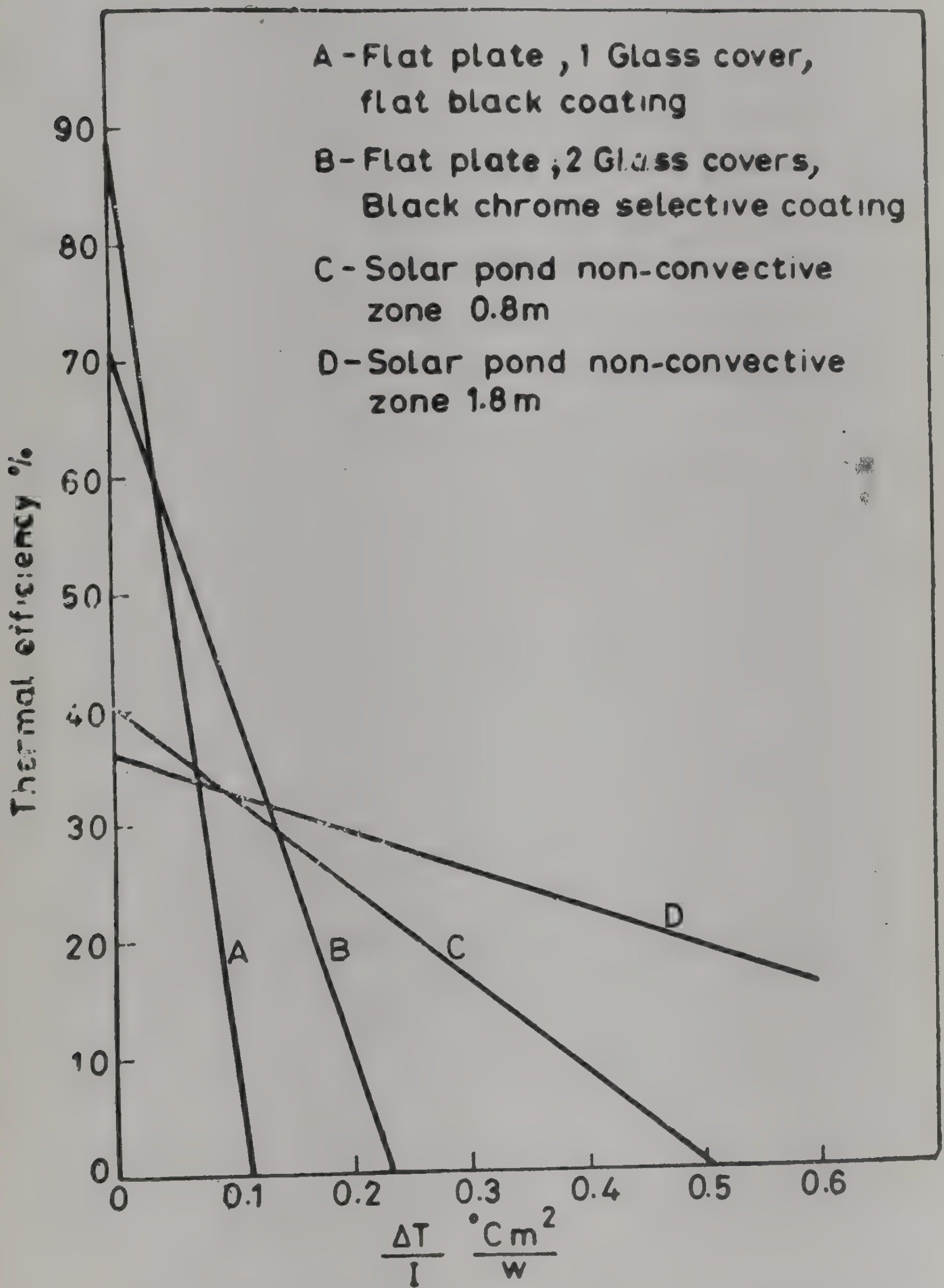

Fig. 4.2 Comparision of solar pond with flat-plate collectors

A comparison of the efficiency of the solar pond with two conventional flat-plate collectors is shown in Fig. 4.2. From this figure we see that the efficiency of solar ponds is higher than that of flat-plate collectors when the temperature differ-rence between the fluid and the ambient is high. This is because the heat loss coefficient of a flat-plate collector is much higher than that of a solar pond. At lower temperature differences the flat-plate collector has a higher efficiency because of its higher optical efficiency.

The maximum temperature attainable in solar ponds using sodium chloride or magnesium chloride is around 100°C. Higher temperatures are not attainable because they would require greater saturation solubility in the lower mixed layer. In Fig. 4.3 the variation of pond efficiency is maximum when the pond depth is 1.2m. As the depth of the pond increases, the thickness of the non-convective layer is also increased, the heat loss from the pond decreases and hence the efficiency increases. As the thickness of the non-convective layer is increased the amount of solar radiation reaching the bottom of the pond decreases. As the thickness of the pond is increased from 0.5 to 1.2m the efficiency increases because the decrease in heat loss is more than the decrease in solar radiation reaching the bottom of the pond. Beyond 1.2m thickness the decrease in solar radiation reaching the bottom of the pond becomes more important than the decrease in heat loss and hence the efficiency decreases. Hence, the thickness of the non-convective layer in a pond must be chosen depending upon the temperature at which the heat is proposed to be extracted. The diurnal variation of temperature in the lower mixed layer depends upon the thickness of the lower mixed layer. For a lower mixed layer with a thickness of 20 cm the diurnal variation is less than 5°C. The thickness of the lower mixed layer is chosen depending upon the amount of energy that needs to be stored in the pond.

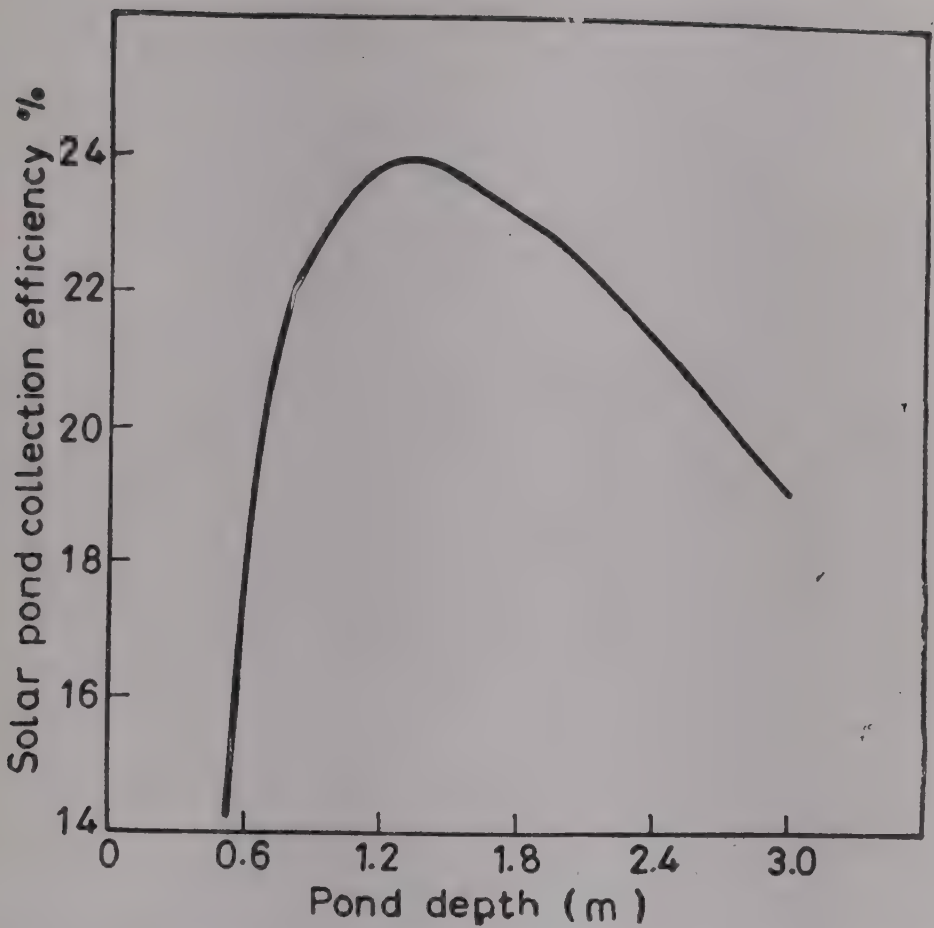

Fig. 4.3 Variation of efficiency with depth for a pond operating °C

4.4 Construction and Maintenance

A large solar pond is generally constructed by flattening a site area and building an embankment around it. In order to prevent loss of salt a lining may be necessary. The most commonly used liners are plastic or elastomeric liners. Some of the liners that have been used are low-density-polyethylene (LDPE), high-density-polyethylene (HDPE), chlorinated polyethylene (CPE), chlorosulfonated polyethylene (HYPALON), Butyl rubber, and polyvinyl chloride (PVC). In India LDPE, HDPE, and PVC are available. PVC is not recommended for

ponds whose temperatures may exceed 60°C. LDPE liners have been widely used in India for lining of irrigation canals, fish ponds, and storing of liquid waste products. LDPE liners can be easily heat sealed in the field. LDPE liners degrade rapidly when exposed to sunlight. Hence, they are usually buried beneath the soil. Hypalon, CPE, and Butyl rubber are superior to polythylene and poiyvinyl chloride as regards resistance to degradation by ultra-violet radiation.

The clarity of pond water has a strong influence on the efficiency of the solar pond. Most dirt falling on the pond will settle quickly and hence will not affect the clarity of the pond. Leaves which float on the pond surface must be removed periodically. Growth of Algae must be prevented because they can reduce the clarity of the pond dramatically The growth of algae can be prevented by chlorination or addition of copper sulphate (few parts per million).

The salinity gradient can be maintained by a combination of surface flushing and addition of salt in the lower mixed layer. Salinity at the surface will increase slowly on account of diffusion of salt from the lower mixed layer. Adequate rainfall, maintains the salinity at the surface at a very low value. During the period without rain, it will be necessary to wash the surface with water and provide an overflow for excess water. Salinity of the lower mixed layer can be increased by passing the water in this layer through a tank containing salt.

Heat can be removed from the pond in two different ways. A heat exchanger can be placed at the bottom of the pond but this will be both expensive and difficult to repair. Alternatively, saline water from the lower mixed layer can be taken out and circulated through a small heat exchanger (outside the pond) and then returned to the pond.

4.5 Applications

Solar ponds can deliver thermal energy at temperatures of upto 90°C with an efficiency of about 20%. This thermal energy can be used for the heating of buildings, domestic hot water supply, drying of agricultural produce, cooling of buildings, and mechanical or electrical power production. For heating of buildings, a pond with an area equal to that of the building should be sufficient to meet the heating needs of the building during winter. In summer, the solar pond can be utilized to cool the building by the use of an absorption cooling system. A 2000 m^2 pond has been built at Miamisberg, Ohio to supply heat for a swimming pool. A 156 m^2 pond has been built at Wooster, Ohio to provide heat for a greenhouse. In Israel, the major effort has been in the conversion of heat stored in the pond, to electrical energy. A 7000 m^2 solar pond has been built at Ein Bokek, on the shores of the Dead Sea. The energy stored in this pond was uttilized to run an organic-vapour Rankine-cycle system. The prime mover of this system was a single-stage impulse turbine running at 18000 rpm. This was coupled to a synchronous alternator through a high speed gearbox. The peak power output of this system was 150 kWe. Tabor (1981) has estimated that it should be possible to build Solar Thermal Power Stations based on Solar ponds which can deliver electric power at a cost of Rs. 1 per kWh. This estimate includes both construction cost and running cost. The thermal energy from solar ponds can be used in multi-flash desalination units operating at moderate temperatures.

In India a solar pond was built at the Central Salt and Marine Chemicals Research Institute in Bhavnagar in 1973. Recently, a 1600 m^2 pond has been built at the same site. The lining used in this pond is 1000 gauge high density polyethylene (HDPE). This liner is covered with a layer of bricks to prevent ultra-violet degradation. A 100 m^2 solar pond was built at the Tata Energy Research Intitute's field research unit at Pondichery. The liner used in this pond was a 1000 gauge

(0.25 mm) low density polythelene (LDPE) sheet. After two yeas of operation the liner developed a leak and the pond was emptied. It is believed that the liner developed a leak on account of the settlement of soil beneath the liner. Since the liner was not buried in this case, it is possible that ultra-violet degradation also contributed to the failure of the liner after two years.

4.6 Conclusions

Solar ponds offer the possibility of collection and storage of solar energy at a low cost. The have distinct advantages over the conventional flat-plate collector in large scale applications because of the absence of elaborate plumbing. The cost of a solar pond (per unit collection area) can be as low as one-tenth of the cost of the conventional flat-plate collector in favourable sites. The ideal site for solar ponds should satisfy the following conditions :

1. Proximity to the place of salt manufacture
2. Soil which is reasonably impervious
3. Latitude below 40 degrees (to reduce angle of incidence of the sun's rays)
4. Large number of clear days
5. Reasonably level site.

If the above conditions are satisfied the cost of the pond can be as low as Rs. 100/m^2.

4.7 Problems, Prospects and Tasks

4.7.1 One of the major important unresolved problems in the operation of solar ponds is the minimising of wind induced mixing. If solar ponds are located in areas prone to cyclones, wind induced mixing erodes the gradient zone rapidly. Studies on the rate of erosion of the gradient are necessary. Different methods of maintaining the salinity gradient should be explored.

4.7.2 The effect of ground thermal conductivity on the efficiency of the solar pond has not been studied extensively. The thermal conductivity is a strong function of the moisture content. During the monsoon the ground is wet and the thermal conductivity increases dramatically. This can result in large thermal losses from the pond.

4.7.3 Most solar ponds so far constructed have used sodium or magneium cholride. Labratory studies of solar ponds based on other salts is worth pursuing.

4.7.4 Location of soils which are naturally impervious will be very useful.

4.7.5 Solar ponds are generally built in large sizes (are greater than 200 m^2). It will be worthwhile to study whether small solar ponds with insulation will be economically viable.

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5. Solar Stills

5.1 Introduction

The need for pure drinking water is very evident, especially in the rural areas where no municipal water purification plants exist. The availability of pure water (i. e. water free from bacteria and parasites) in contrast to the present practice of using water from insanitary water bodies like tanks and small lakes, where water borne bacteria and parasites breed profusely, would go a long way to improve the health of rural inhabitants. An obvious requirement for treating water is when it is brackish and hence unsuitabie for drinking or washing. The use of solar energy for distilling water normally accquired from such contaminated and/or unpotable sources appears to be a very attractive application. Another possible use is in the drying of biogas sludge, where again the water in the sludge can be removed by using solar energy to distil the water out of the sludge, and collecting the water back for recycling or for other uses.

The hydrologic cycle presently provides all the fresh water, by way of large scale solar distillation. There are four essential phases :

1. Production of vapour from water bodies by the heating of water bodies by solar radiation and the resulting evaporation from the surface of these water bodies.
2. Transport of this vapour in air to cooler regions by convective winds, which are caused by the unequal heating of different regions by the sun.
3. Condensation of vapour resulting in precipitation as rain and snow.

4. Return of water and melted snow by means of rivers, back to oceans, lakes and other large bodies of water.

Solar stills reproduce the first three phases on a small scale to generate pure water. The simplest type of solar still is a basin type solar still constiting of a shallow blackened basin containing the water to be distilled, over which a transparent cover is sloped, so as to permit the water condensing on the cooler transparent cover to slide down the surface, towards a collection trough where the distillate is collected as shown in Fig. 5.1. Solar energy is absorbed by the water and the basin liner, thus heating the water, and since the cover is much cooler than the water surface, there results a convection current of vapour from the water surface towards the cover where condensation of vapour occurs. Such simple stills are not very efficient because they require solar energy inputs equal to several times the latent heat of water distilled, whereas in other distillation plants running on fossil fuels or electricity or nuclear energy, the supply of heat energy amounts to only a small fraction of the latent heat of water distilled.

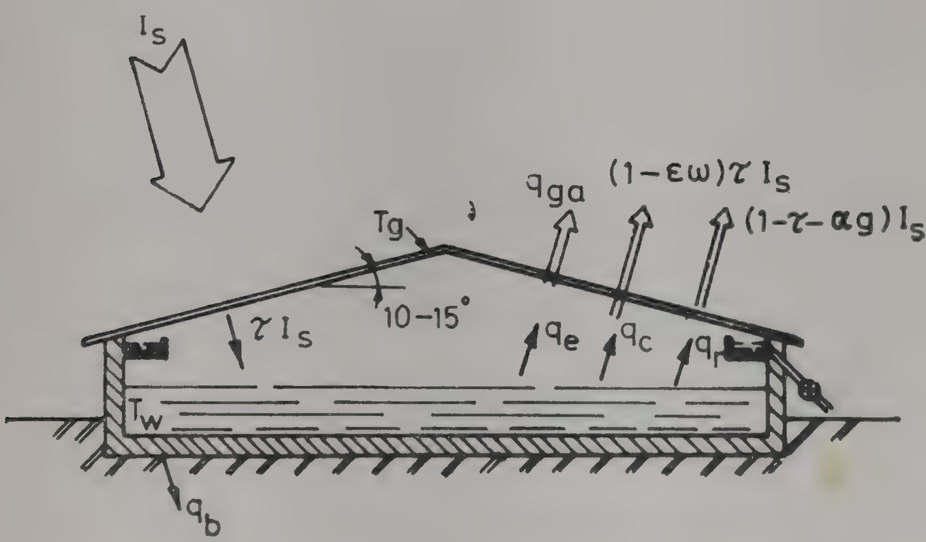

Fig. 5.1 Basin type Solar Still

5.2 Analysis

An estimate of the amount of water that can be distilled per unit area of the still is made on the basis of a simple analysis shown below. Fig. 5.2 schematically shows the thermal circuit of a solar still, and Fig. 5.3 shows the various heat fluxes.

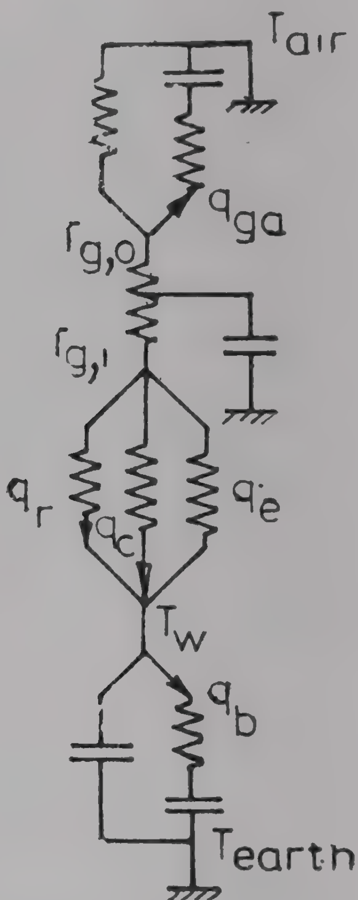

Fig. 5.2 Thermal circuit of Solar Still

1. Heat balance on basin water

$$\tau \alpha_w I_s = q_b + q_e + q_r + q_c + C_{wb}\,(dT_w/dt) \tag{1}$$

2. Heat balance on glass cover (2)

$$q_e + q_r + q_c + \alpha g I_s = q_{ga} + C_{gs}\,(dT_g/dt) \tag{3}$$

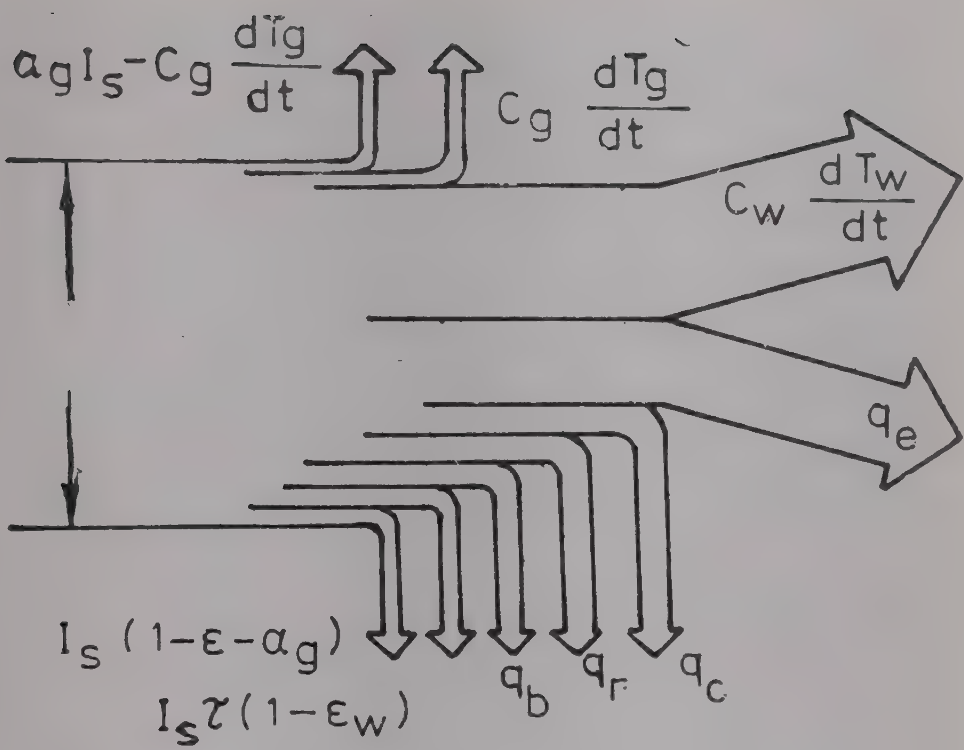

Fig. 5.3 Heat Flow in a Solar Still

3. Heat balance on basin and cover assembly (by adding (1) and (2) as above).

$$\tau\alpha_w I_s + \alpha_g I_s = q_{ga} + q_b + C_{wb}(dT_w/dt) + C_{gs}\,(dT_g/dt) \quad (3)$$

4. The radiative heat flux q_r is given by [1]

$$\begin{aligned} q_r &= F_s\,(T_w^4 - T_g^4)\varepsilon\sigma \\ &= (0.9)\,(T_w^4 - T_g^4)\varepsilon\sigma \end{aligned} \quad (4)$$

where, F_s is the shape factor between the cover and the water surface.

5. The convective heat flux q_c is [1] :

$$q_c = h_c\,(T_w - T_g) \quad (5)$$

where, h_c is the natural convective heat transfer coefficient that is related to the non-dimensional parameters ; Nusselt

number Nu, Grashof number Gr, and the Prandtl number Pr, by the following relations

$Nu_x = K\,(Gr.\ Pr)^n$, $Nu = h_c x/k$; $Gr = \beta g \triangle T x^3/\nu^2$;
$Pr = \mu c_p/k$

Here ρ is the density, μ and ν the dynamic and kinematic viscosity, k the thermal condutivity, c_p the heat capacity at constant pressure, β the expansion coefficient of air, g the acceleration due to gravity, x the spacing between the cover and the water level, n and K are correlation coefficients.

For large Gr, i.e., $10^7 > Gr > 3.2 \times 10^5$, $K = 0.075$ and $n = 1/3$

$$\text{thus,} \quad h_c = K \left\{ \frac{g\,\beta \triangle T}{\nu^2} \cdot \frac{\mu c_p}{k} \right\}^{1/3}$$

$$= 8.84 \times 10^{-4} \{(T_w - T_g) + (p_w - p_{wg}).$$
$$T_w(2.65 p_T - p_w)\}^{1/3}\ (T_w - T_g) \qquad (6)$$

where, p_w and p_{wg} are the actual and saturation vapour pressures near the surface of water, whose temperature is T_w.

This relation is derived by treating $\beta \triangle T$ as a variable within the still.

6. The heat flux of evaporation q_e is :

$$q_e = m_d L \qquad (7)$$

where m_d is the rate of distillation.

By using the analogy between mass and heat transfer the evaporation rate m_d is related to the natural convective heat transfer, as

$$m_d = (18.41)\ h_c\ (p_w - p_{wg}) \qquad (8)$$

Then q_e can be expressed as :

$$q_e = 6.8742 \times 10^{-9} \{q_c/(T_w - T_g)\}\ (p_w - p_{wg})\ L \qquad (9)$$

7. The conduction loss through the bottom of the still q_b is:

$$q_b = h_b\ (T_w - T_a) \qquad (10)$$

8. Heat flux from transparent cover

$$q_{ga} = h'_c\ (T_g - T_a) + g\ (T_g^4 - T_{sky}^4) \qquad (11)$$

where, the sky temperature can be given by any one of several empirical relations [1], for example:

$$T_{sky} = T_{air} - 11°C$$

$$h'_c = 0.028\ (Re)^{0.8} k/x$$

L is the width of still

$$Re = VL/(\nu)$$

As could be seen from this analysis, the simultaneous solution of these equations yields quantities of interest like q_e, etc. But even without solving the equations completely, certain conclusions can be drawn by an examination of the relations:

1. For a given solar influx, T_w can be increased if C_{wb} is lower or depth of water in the still is lower.

2. With higher T_w, higher q_e will result. Hence shallow stills are more productive.

3. The need for insulation all around is again seen to be necessary for reducing q_b, which in turn will lead to higher T_w. Insulation of upto 2.5 cm thickness of a good insulator is recommended.

4. The effect of cover temperature T_g has been analysed by several research workers [2, 3]. It is found that for a given $(T_w - T_g)$, higher T_w still causes an increase in the evaporative heat flux, so that the efficiency increases with increasing water temperature.

The maximum efficiency possible for a solar still of the type described can be estimated by assuming :

(a) no heat losses : $q_b \simeq 0$

(b) heat capacity of water to be very small, so that all the solar influx absorbed is transfered to the cover through the conducting water and that this transfered heat is then dissipated through the cover. The maximum efficiency achievable is about 60%, while a practical upper limit would be about 50%.

The Fig. 5.3 shows the performance of a practical still. Normally the output of a still is expressed as so many litres of water per m^2 per day. The maximum yields are about 5 litres/m^2-day. In actual practice many factors cause a reduction in the yeild of distilled water. Some of these are transmission losses through the cover, heat losses from the sides, influx of air in the still. The leakage of air is extremely deleterious to the performance of the still. The leakage of air increases with temperature and with wind velocity. Hence, sealing of the still is of utmost importance. From a study of many stills it is found that the daily yeild of a still is a slightly non-linear function of the solar insolation. A general relation proposed is [3] :

$$P = (1.286 \cdot 10^{-3})\ (I_s)^{1 \cdot 4} \text{ litres/m}^2\text{-day} \qquad (12)$$

where, I_{av} is the average 24 hour average solar insolation in W/m^2 ($\simeq$ 260 to 300 W/m^2). This correlation predicts the performance to fall within the range $\pm$P 25%, when I_{av} = 250 W/m^2.

In general, roof type solar stills are rectangular shallow troughs about 0.2m deep and 1.5m wide and upto 25m in length. The roofing material is mainly glass. The cost of the still is mainly made up from the cost of the land, its excavation, levelling and the laying of an insulation bed and a basin impervious to water, a structure to support the glazing and of course the glazing itself. The average cost is Rs. 500 to 1000/m^2.

5.3 Type of Solar Stills

For a very long time solar distillation and desalination plants have been used in many parts of the world. One of the earliest was a large basin type solar still put up near Las Salinar in Chile in 1872 and had an area of 4700m^2. There was a surge of interest in solar still development during the second world war when inflatable plastic stills were made for use in emergency life rafts of the Navy and Air Force. These were made of an inflatable plastic envelope and contained a felt pad saturated with sea water and a distillate collector bottle connected to the bottom of the plastic envelope. This device was floated on sea and distillation was carried out by collecting solar radiation incident on the felt pad. Dr. Maria Telkes, the developer of this device then further investigated in depth solar desaturation and distillation by trying out various configurations. The conclusion was that the solar stills could not compete with any other form of distillation because of its high cost. Fig. 5. 4 shows various configurations of solar stills possible.

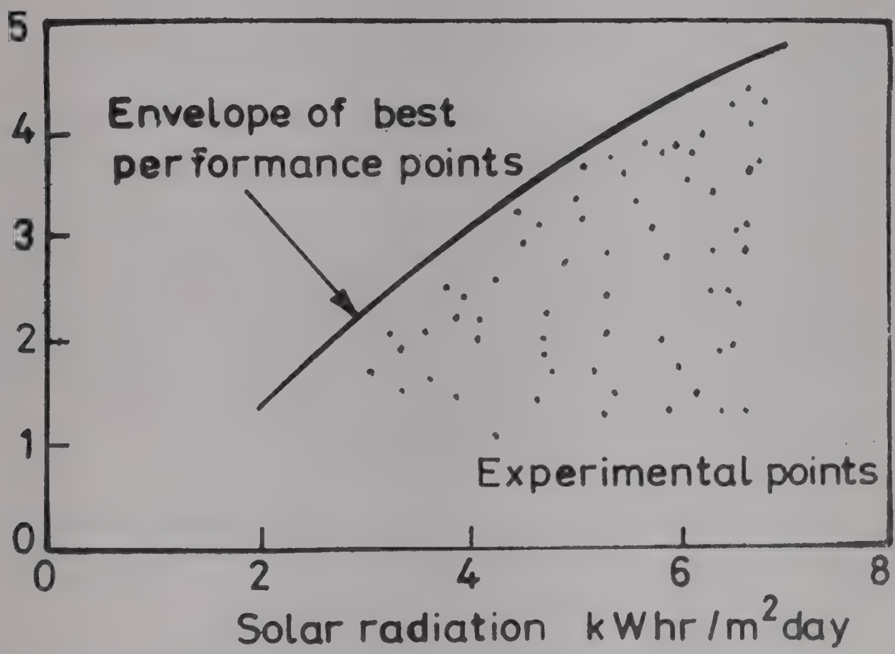

Fig. 5.4 Performance of Solar Stills

Many variations in the design of the basin type still have been tried, to improve its performance. The most common one is to introduce a slightly sloping floor with many dams built in. This is done to avoid the problem of accurately levelling the floor, which is necessary to prevent the formation of dry patches on the floor, since the depth of water in the basin is very small. Another innovation is the use of a tilted tray and tilted wicks. These wicks could be made of porous materials like gunny, cotton mats etc., and help in the sense that they distribute the water uniformly and also have a greater surface area than that offered by the floor alone. Another improvement suggested is to dissolve a dye substance in the water being distilled, to increase the solar radiation absorption. It may be stated that these changes can be only marginal improvements, since, it is basically the concentration gradient of condensation. Diffusion and natural convection of vapour from the hot pool to the cooler cover where condensation occurs puts an upper limit on the rate of distillation. Thus, having a very small gap between the water level and glass, provision of a good air seal, use of a shallow pool of water are all the obvious steps necessary for good performance.

5.4 Problems, Prospects and Tasks

In a solar still heat is supplied to evaporate the water and then this vapour condenses on the glass or plastic cover. The heat of condensation released at this place is unfortunately not reused, instead it is to be dissipated into the surroundings as heat loss. If this heat could be reused it is then possible to obtain efficiencies much higher than what is practicable in the simple basin type still. In all distillation plants using fossil fuel or other conventional heat sources, the energy requirement is much lower because of the reuse of the heat of condensation. Some solar devices where "multiple-effect distillation" is accomplished, have been developed. Further work in this direction would go towards increasing the yields of solar stills.

The cost of solar distilled water is rather high because of the high cost of materials used in stills. Assuming an average 1 to 1.2m^3 of distillate/year, and a capital cost of Rs. 300 to Rs. 500/m^2, the cost of distilled water for a unit with a 10 year life would be Rs. 25 to 40/m^3 or the cost of capital amortization of the system alone. Maintenance and operation costs are extra. There are no obvious economies of scale. This could be compared to the cost of fresh water ranging from Rs. 0.20 to Rs. 2/- for 1000 litres supplied by municipal bodies, and about Rs. 3 to 5/- for thousand litres when distilled by using coal. Unless the cost of solar still comes down to about Rs. 100/m^2 and has a life of 20 years (when the cost of solar distilled water cost will be under Rs. 10/1000 litres) the future of solar stills is rather bleak. Attempts at reducing the cost and increasing the efficiency are thus imperative if solar stills are to become competitive.

5.4.1 The trough material can be mild steel, stainless steel, wood, concrete or masonry, etc. But for making the trough impervious to water when masonry, concrete or other material is used a liner, is required. This could be a plastic sheet (black polyethylene) or butyl rubber (rubber is preferred due to superior aging, elastic and sealing properties). Glass supports are made of masonry, concrete, wood, aluminium or other material. Of course, it is possible to use plastic sheets for covering. But the problem of deterioration of plastic under constant sunshine can be overcome, only if specially formulated plastic having UV resistance is used. Furthermore, plastic sheets tend to sag in the middle thus causing the water condensate to fall back into the basin. When plastics are used the roof slope should be rather high (more than the 10-15° for glass). Another reason for a higher slope is that water is less wettable than glass so that many individual, small drops are formed as opposed to glass which is well wetted with water, so that drops agglomerate very easily.

5.4.2 Heat losses from the bottom and sides of the trough should be minimised by providing proper insulation

which could be plastic foam - styrofoam or polyethylene foam, etc., or other less expensive material. Study of these aspects and the basic theory of vapour transport in the still with a view to enhancing the diffusion rates are some of the directions where investigations may be undertaken.

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6. Solar Engines

6.1 Introduction

Solar energy can be converted to electrical energy or mechanical energy in two different ways. For example, it can be directly converted to electrical energy by photovoltaic devices. Alternatively, solar energy can be converted to mechanical energy through heat engines. The direct conversion of solar energy to electricity presents itself as an elegant solution, since there are no moving parts involved in the conversion process. The capital cost of solar electric systems using photovoltaic devices is presently around Rs. 100/- per peak watt. This is prohibitively expensive. There are indications that the cost may come down dramatically when these devices are mass produced. The conversion of solar energy to mechanical energy, through heat engines though more cumbersome, is less expensive than solar-electric systems using photovoltaic devices.

6.2 System Efficiency

The efficiency of conversion of solar energy to mechanical energy depends upon the efficiency of collection of solar energy, and the efficiency of the heat engine. The efficiency of any solar energy collector can be written as :

$$\eta_c = \eta_o - [U_c\,(T_c - T_a)/(CRI_c)] \qquad (1)$$

where, η_c = thermal efficiency of the collector

= (thermal energy collected)/(solar energy incident)

where, η_o is the optical efficiency of the collector, U_c is the collector heat loss coefficient, CR is the concentration Ratio = (aperture area) / (receiver area), T_a is the ambient temperature.

The efficiency of the heat engine depends upon the specific thermodynamic cycle that is used. From the second law of thermodynamics, we know that the best heat engine is the one which follows the Carnot cycle. The efficiency of the Carnot cycle can be written as :

$$\eta_{carnot} = 1 - T_r/T_s \tag{2}$$

where, T_r is the temperature of heat rejection in the cycle, and T_s the temperature at which heat is added in the cycle. For simplicity, we can take T_r to be equal to T_a, the ambient temperature, and T_s to be equal to T_c, the collector temperature. The efficiency of all real cycles is lower than that of the Carnot cycle ; and the efficiency of these cycles depend upon T_c and T_a in a manner similar to the Carnot cycle. For the purposes of the present discussion we will assume that the heat engine follows the Carnot cycle. The overall efficiency of the system η_{sys} is a product of the collector efficiency and the heat engine efficiency.

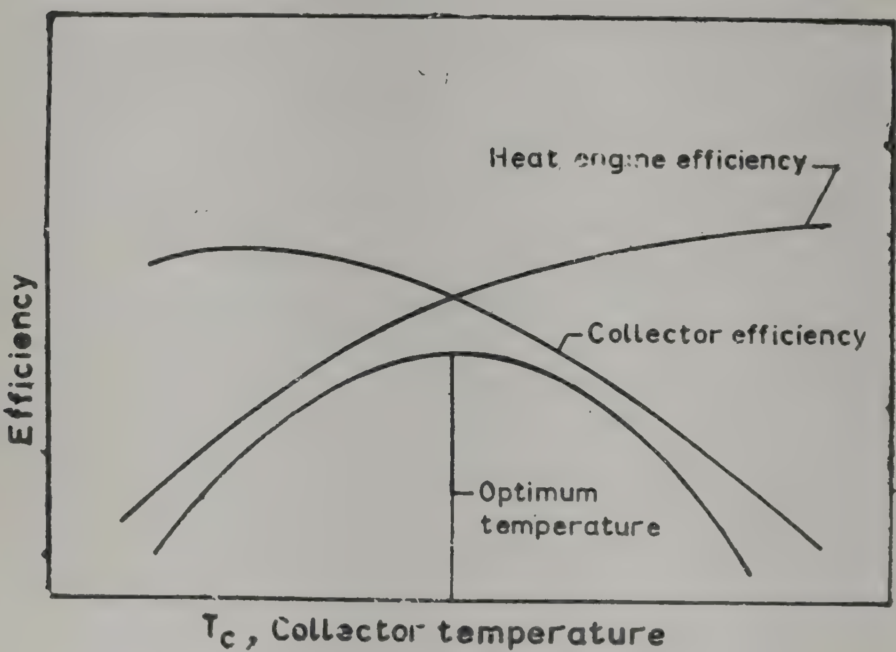

Fig. 6.1 Variation of efficiency of engine with collector temperature

Hence, $\eta_{sys} = \eta_{cycle}\, \eta_c$ (3)

$$= \left(1 - \frac{T_a}{T_c}\right) \left(\eta_o - \frac{U_c}{CR\, I_c} (T_c - T_a)\right) \quad (4)$$

From the above equation we see that η_{cycle} increases as T_c increases while η_c decreases as T_c increases. The variation of η_{sys} with T_c is qualitatively shown in Fig. 6.1.

We see from Fig. 6.1. that for every collector there is an optimum temperature at which the system efficiency is maximum. We can obtain the optimum temperature from the above equation by setting

$(\delta \eta_{sys})/(\delta T_c) = 0$

Hence,

$$\frac{T_{c,\,opt}}{T_a} = (1 + \eta_o CR I_c / U_c T_a)^{1/2} \quad (6)$$

The above result is obtained by assuming a mean value for U_c (which is valid if U_c is not a strong function of T_c). Let us consider a few examples to illustrate the usefulness of the above result.

6.2.1 Flat-Plate Collector (with two glass covers)

Here $CR = 1.0$, $\eta_o = 0.8$, $T_a = 300K$, $I_c = 800 W/m^2$

Assuming, $U_c \simeq 5 W/m^2\ °C$, we get $T_{c,\,opt} = 357 K$ (84°C), $\eta_c = 44\%$, $\eta_{cycle} = 16\%$, $\eta_{sys} = 7\%$.

Since, actual heat engines have a much lower efficiency than the Carnot cycle, the overall efficiency of conversion of solar energy to mechanical energy using flat-plate collectors has in practice, never exceeded 2%. More than 70% of the capital cost of solar thermal power systems is due to the collectors. Since the overall efficiencies of systems using flat-plate collectors is very low, the capital cost of the system

is extremely large. For example, assuming that the cost of flat-plate collectors is Rs. 1200/m^2 (an optimistic estimate), and this contributes about 75% to the system cost, the cost of the system is Rs. 100/- per peak watt. For this estimate we have assumed that the system efficiency is 2% and the peak solar radiation normal to the collector is 800W/m^2. The above system cost is the same as that for photovoltaic devices. As already indicated there is a strong possibitity for dramatic cost reduction in the case of photovoltaic devices. This is not the case with flat-plate collectors. The only possibility of having a large inexpensive solar flat-plate collector is through the use of a large body of water to serve as a collector. This possibility is exploited in a solar pond. There is a strong possibility of building solar ponds whose cost is below Rs. 300/m^2. In such an eventuality, conversion of solar energy to mechanical energy through solar ponds and heat engines may be more economical than photovoltaic devices.

6.2.2 Stationary Concentrators

The primary reason for the low overall efficiency of the solar-thermal power systems (STPS) using flat-plate collectors is the low optimum operating temperature (80-90°C). The optimum operating temperature is low because the heat losses from flat-plate collectors increase rapidly above this temperature. In solar concentrators the heat losses are much lower than in flat-plate collectors because the receiver area (through which heat loss occurs) is much more lower than the aperture area. The parabolic trough or paraboloid dish concentrators require single and two-axis tracking respectively. This adds to the complexity and cost of the system. A new concept has emerged recently which enables one to build concentrators which require occasional tilting but no daily tracking. These concentrators are called stationary or non-imaging concentrators. One example of this type of concentrator is the compound parabolic concentrator. The maximum concentration ratio

achievable with these concentrators is around 10. Consider a compound parabolic concentration with a concentration ratio of 3. Assuming, $\eta_o = 0.72$, $U_c = 3 W/m^2 \, ^\circ C$, $I_c = 700 \, W/m^2$, $T_a = 300K$, we get $T_{c,\ opt} = 480K$ (207°C) (only part of diffuse radiation can be accepted by this one).

$\eta_c = 46\%$, $\eta_{cycle} = 37.5\%$, $\eta_{system} = 17\%$.

In practice, the system efficiency will probably be around 7%. The cost of compound parabolic concentrators will probably be around Rs. 1500/m^2 (i.e., little higher than flat-plate collectors). Assuming once more that this constitutes 75% of the system cost, we can estimate the system cost to be (for $\eta_{sys} = 7\%$ $I_c = 700 \, W/m^2$) Rs. 40 per peak watt. This cost is lower than that for the system based on flat-plate collectors or photovoltaic devices. Since the technology for the mass production of compound parabolic concentrators is still evolving it is difficult to assess whether our estimate of their cost (Rs. 1500/m^2) is reasonable. At present the possibility of building small solar thermal power plants ($\langle$10 kW) using compound parabolic concentration looks attractive.

6.2.3. Single-Axis Tracking Concentrators

These concentrators can have concentration ratios in the range 10 to 50. The single-axis tracking can be done by stepper motors with provision for feed back through photovoltaic sensors. These are not mass produced and hence their cost is difficult to estimate. The most common examples are parabolic trough mirror concentrators and linear Fresnel lens concentrators. Mirror concentrators and Fresnel lenses (made of plastic) must be kept dust-free during their operation. The optical efficiency of these concentrators, η_o is around 0.6. Assuming CR=25, $U_c = 10 \, W/m^2 \, ^\circ C$ (because the receivers are at a much higher temperature), $I_c = 600 \, W/m^2$ (because these concentrators can utilise only beam radiation) and $T_a = 300K$, we get $T_{c,opt} = 600K$ (327°C) and $\eta_c = 40\%$, $\eta_{cycle} = 50\%$, $\eta_{sys} = 20\%$. In practice, the system efficiency will be around 10%. It is difficult to estimate the cost of single-axis tracking concentrators when mass produced. It will probably be

around Rs. 2250/m^2. This will mean a system cost of Rs. 50/- per peak watt (for $I_c = 600$ W/m^2, $\eta_{sys} = 10\%$). We find that the system cost of stationery concentrators is about the same In such a case stationery concentrators will be preferred because they have fewer maintenance problems.

6.2.4. Two-Axis Tracking Concentrators

These can be either paraboloid, dish concentrators or a field of mirrors (called Heliostats) focussing solar energy to a single point on the power tower. The concentration ratios are usually in the range 100-1000. On account of the high concentration ratios the thermal losses from these concentrators are very low. Hence the efficiency of collection is primarily controlled by the optical efficiency η_o. The optical efficiency depends upon the reflectivity of the mirror (or transmittivity of the lens), accuracy of the mirror (or lens), and the accuracy of the two-axis tracking. Collection efficiencies in the range of 60 – 70% is possible. The cost of paraboloid dish concentrators (based on the cost of Radar dishes) will probably be around Rs. 3000/m^2. The highest temperature achievable in these concentrators is determined by materials which can withstand high temperatures. Temperatures above 800 K will not be possible at present on account of the non-availablity of materials which can withstand high temperatures for prolonged periods. With a collection efficiency of 60% and Carnot cycle efficiency of 62.5% (with T_c800 K and $T_a = 300$K) the system efficiency will be 37.5%. In practice a system efficiency of 25% can be attained. With $I_c = 600$ W/m^2 (beam radiation) and concentrator cost Rs 3000/m^2 (assuming this to be 75% of the system cost) the system cost is Rs. 26 per peak watt. The two-axis tracking concentrators thus seems to be the most attractive choice. There is, however, a lot of uncertainity about their cost and reliability. Large solar-thermal power systems (greater than 100 KWe) based on two-axis tracking Heliostats and conventional steam turbines have been built in the U.S.A. and Europe.

6.3 Choice of Thermodynamic Cycle and Working Fluid

A large number of thermodynamic cycles can be utilised in heat engines of solar thermal power systems. The most commonly chosen cycle is the Rankine cycle. This is because the efficiency of the Rankine cycle can approach the Carnot cycle, and secondly a lot of experience already exists in the utilisation of this cycle. The other commonly used cycle is the Stirling cycle. This cycle has not been used in conventional thermal power plants and hence not much information exists about the efficiencies that can be attained with this cycle. Theoretically, a Stirling cycle with regeneration can have efficiencies approaching the Carnot cycle. Heat engines based on the Stirling Cycle are more compact than those based on the Rankine Cycle. The working fluids used in the Stirling cycle are air, hydrogen and helium. In the Rankine cycle, the choice of working fluid depends upon the maximum temperature achieved in the cycle and the prime mover used. In solar energy conversion systems using flat-plate collectors the maximum temperature in the cycle will be around 80-90°C. Hence a working fluid with a low boiling point is needed. The fluids suitable for this purpose are halogenated hydrocarbons (freons), pentane, sulphur dioxide and ammonia. Of these Freon-11, Freon-12, and Freon-114 are most popular because of their long use in the air-conditioning and refrigeration industry. Their working fluids can be mixed with lubricants, are non-toxic, non-flammable and non-corrosive. Freons are also used in solar thermal power systems with compound parabolic concentrators or single-axis tracking concentrators. In power-towers (two-axis tracking heliostats concentrating solar energy on a receiver placed on a tower) the temperatures in the receiver are above 500°C band hence the Rankine cycle with water as the working fluid is used. In parabolic dish concentrators a portable Stirling engine (with air as the working fluid) is mounted at the focus of the concentrator (see Fig. 6.2)

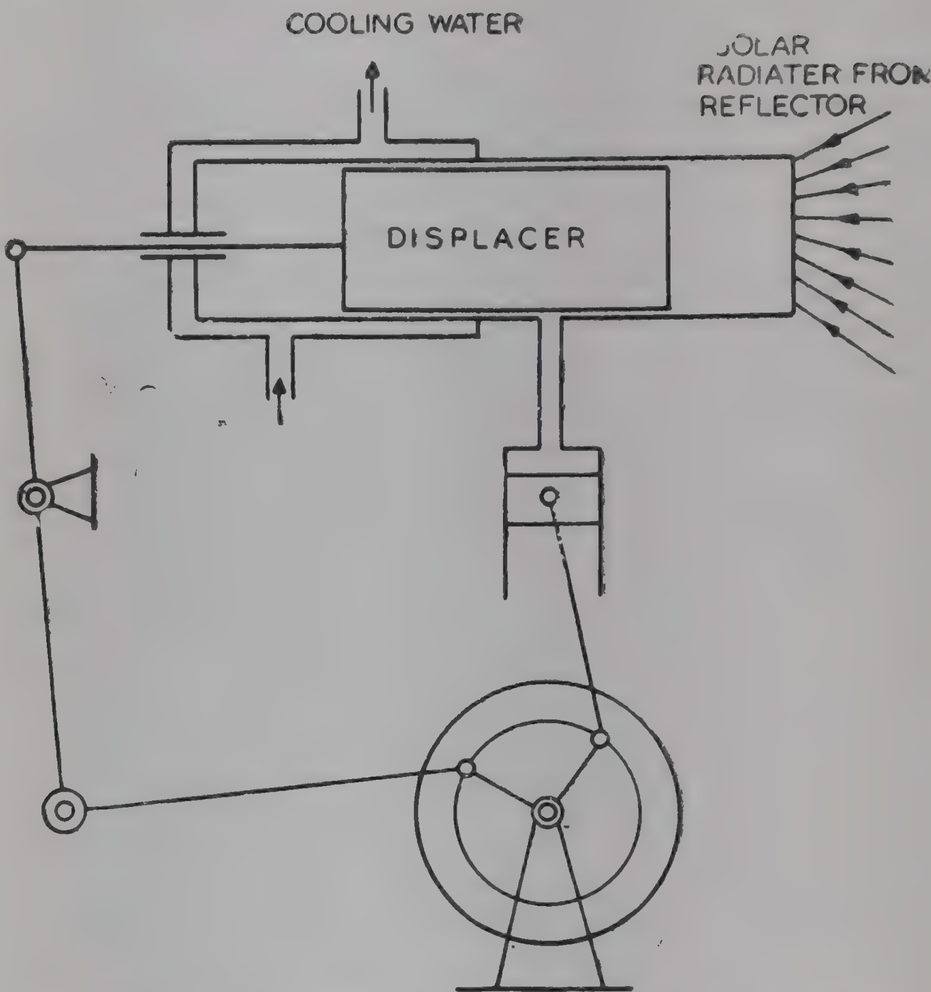

Fig. 6.2 Schematic diagram of closed-cycle, hot-air engine.

6.4 Prime Movers

In a Stirling cycle the prime mover is a reciprocating engine. In the Rankine cycle the prime mover can be a turbine, reciprocating engine or a positive-displacement rotary machine. For solar thermal power plants with a power output above 50 kW, turbines are preferred. Turbines are highly reliable machines with low fractional losses. The efficiency of a turbine reduces rapidly when operated at off-design loads or speeds. In small solar thermal power plants with small storage the prime mover may have to work at off-designs speeds and

loads. In addition, in small power plants where single stage impulse turbines are used, the operating speeds are very high (around 20,000 rpm). Hence a reciprocating engine or positive-displacement rotary machine is preferred for small solar-thermal power plants. Small reciprocating engines or positive displacement rotary machines are not readily available and hence need to be made to suit the requirements of the organic vapour Rankine cycle. Some of the positive-displacement rotary machines which have been used are Lysholin expanders, screw expanders, spiral expanders and vane expanders. These machines are usually expensive because they are made specifically for Rankine cycles. Of the other reciprocating engines manufactured for the internal combustion engines market, reciprocating compressors used in refrigeration systems can be modified and used in the organic vapour Rankine cycle. Some examples of solar-thermal power system operation around the world are discussed in the next section.

6.4.1 Case Studies

6.4.1.1 SOFRETES Engine

The Societe' francaise d'e'tudes thermiques et d'e'nergie solaire (SOFRETES) has installed many irrigation pumps run by solar-thermal power systems. Majority of these installations are in Africa and Mexico. These systems consist of a 60m^2 flat-plate collector which delivers hot water at 70°C. This generates Freon-11 vapour at a pressure of 3 bar, in the evaporator. The Freon vapour expands in a reciprocating engine which runs a 1 kW irrigation pump. The cost of this system is around Rs. 1 lakh. At present irrigation pumps run by solar-photovoltatic systems are more reliable and economical than systems based on flat-plate collectors and heat engines.

6.4.1.2 MBB Engines

Messerschmidt-Bolkow-Blohm GmbH, Ottobrunn, Federal Republic of Germany have developed a 10 kW solar-thermal

power plant. Flat-plate collectors (with two glass covers) of area 700m², have been used. The working fluid is the refrigerant Freon-114, which leaves the evaporator at a temperature of 90°C and pressure of 10 bar. This vapour expands in a screw-expander. A 10 kW power plant using flat-plate collecters manufactured by Bharat Heavy Electricals Limited (BHEL) and the Rankine Cycle developed by MBB was installed at the Indian Institute of Technology, Madras.

6.4.1.3 MAN Engine

Masschinenfabrik-Augsburg-Nurnberg AG (MAN) in the Federal Repubic of Germany have developed a 10 kW solar-thermal power plant using parabolic trough concentrators and reciprocating steam engines. The power plant consists of 72 parabolic trough concentrators with a total aperture area of 180 m². Water is evaporated in these concentrators and steam at 200°C is generated at a pressure of 15 bar. The steam expands in a conventional reciprocating steam engine and produces a peak output of 10 kW. The efficiency of the collectors is 50%, the heat engine 12% and the overall efficiency of the system is 6%. The cost of this system is estimated to be Rs. 30 per peak watt.

6.4.1.4. Farber Engine

Erich. A. Farber of Solar Energy and Energy Conversion Laboratory of the University of Florida, U S.A. has developed a Stirling engine (with air as the working fluid) for use with paraboloid dish concentrators. The engine was made by modifying a 1 kW gasoline engine. A standard army search light (paraboloid dish 1.6m diameter) was used as the concentrator. The Stirling engine was placed at the focus of the concentrator. The engine gave a maximum output of 150 watts at 150 rpm. The overall efficiency of the system was 9%. The main advantage of this system is its simplicity, compactness, and the fact that no special working fluid is necessary (see Fig. 6.2).

6.4.1.5. Barstow Power Tower System

A 10 MWe demonstration solar-thermal power plant has been built at Barstow, California. The plant has 2350 heliostats each with a surface area of $31 m^2$. The heliostats direct solar energy to a receiver which is located on top of a 100m high tower. Water is evaporated in the receiver and steam is produced, which runs a conventional steam turbine. The overall efficiency of this plant is around 20%. This kind of solar-thermal power plant can be connected to the power-grid for supplying peaking-power requirements.

6.4.1.6. Eurelios Power Tower System

A 1 MWe central receiver power plant in Adrano, Sicily, Italy was put into operation in December 1980. This power plant has two types of heliostats, one with area $23 m^2$ and the other $52 m^2$. The total mirror area is $6216 m^2$. The receiver is located on top of a 55m tower and has an aperture of 4.5m. Water is evaporated in the receiver and steam at 512°C and 64 bar, leaves the receiver at a rate of 4860 Kg/hr. The overall efficiency of the system is around 16%.

6.4.1.7. Solar Pond Power Plant

A 150 kWe power plant using the heat absorbed by $7000 m^2$ solar pond at Ein Bokek (on the shore of the Dead Sea) in Israel was commissioned in December 1979. The temperatures reached at the bottom of the pond was 90°C. A Rankine cycle power system utilised this heat and evaporated an organic vapour which expanded in a single-stage impulse turbine at 18,000 rpm. The speed was reduced to 3000 rpm (by gear reduction) to drive a synchronous alternator.

6.5. Conclusions

We have seen that a large number of alternatives exist for conversion of solar energy to mechanical energy through heat

engines. Of these the large scale ($>$ I MWe) systems based on heliostats, medium-scale (100 KWe-1 MWe) systems based on paraboloid trough concentrator systems, and small scale systems based solar ponds or stationary concentrators appear the most promising. Whether any of these systems become economically viable depends upon cost-reduction achievable in mass-production and the rate of increase of cost of fossil fuels.

6.6 Problems, Prospects and Tasks

The prime mover of a solar thermal power system can be a reciprocating engine, rotary expander, or turbine. At present these prime movers are not readily available for solar thermal power systems with output less than 100 kW. This has been one of the major hurdles in the popularisation of small scale thermal power systems. Each prime mover has to be customed made for a specific output. Hence the cost of these prime movers is probhitive.

6.6.1 An alternative, in the short term, is to try to adapt reciprocating internal combustion engines, that are available in small sizes to suit the requirements of solar thermal power systems. This has been attempted by many investigators with limited success. The major problem has been leakage of of the working fluid past the valve.

6.6.2 It is possible to modify a refrigerant compressor or screw compressor so that they can function as engines. This would require a modification of the valves.

6.6.3 There is still a lot of scope for improving the efficiency of a steam engine which can be used in conjunction with a concentrator.

6.6.4 There also exists the possibility of using air motors (used in the mining industry) as prime movers in solar thermal power systems.

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7. A Critique of SPP Projects on Solar Energy

In the earlier volume on Perspectives in Technology : Solar Energy 1, a review of some of the SPP Projects dealing with Solar Energy was given. Here we review some more projects. The objectives of the review are still the same. They are :

(1) to list the projects already completed so that this serves as a catalogue

(2) to highlight the good points and weaknesses of the projects

(3) to examine the objectives and approach of the projects and examine how close the results are to the proposed objectives and

(4) to present a brief critique.

Here again the major observations are virtually identical to what were presented earlier. It is worthwhile to repeat these observations here also. It is essential to devote much attention to formulating the project, viz, identifying the principal aim, the methodology or approach to be adopted towards reaching these aims, the results expected, the facilities available and the fabrication that is necessary for carrying out the project. It may be necessary to carry out a fair bit of theoretical study before setting down the goals of the project, so that they are realistic in the context of the limited time, finances and facilities that are available. It should also be borne in mind that the aim of these projects is mainly educational - i. e., they should teach the student some concepts of design and analysis of a practical nature, rather than merely

being abstract studies. The importance of carrying out performance tests should never be forgotten, an aspect which has received scant attention in the majority of cases. There are many projects wherein work of a similar nature has been carried out earlier by other students. While there is nothing wrong in attempting such work the objectives must be very clear, taking into account the earlier efforts and learning from their successes and failures.

Another aspect that is of importance is that in planning and executing the projects, it is not essential that only inexpensive devices be examined. Obviously, any interesting idea is to be first carefully investigated, and its viability established technically. Only after this should the economics of the idea be examined.

7.1 Concentrators

A few projects dealing with solar concentrators have been carried out. These have been :

(1) non-imaging type (Solar Oven), using an 8 sided conical reflector

(2) non-imaging type (Solar autoclave) using a regular conical reflector and

(3) imaging type of concentrator (Solar Milk Pasteuriser) - Parabolic cylindrical trough.

These projects have not been able to achieve all their objectives. The reasons for this are several.

It should be realized that as soon as a concentrating optical element is attached to a device, it does not automatically improve the performance of a solar thermal device. Firstly, since the acceptance angle of the device is limited, radiation coming only within this angle is accepted, as opposed to a flat-plate collector whose acceptance angle is 180°. So, if radiation incident from outside this acceptance region is

not utilized at all. Furthermore, the concentration ratio of the devices used is not very large - this means that the reduction in heat loss resulting from the reduced area of the absorber is not very large compared to a flat-plate collector. Another aspect is the reflectivity of the elements used is about 65%, or so, then this becomes virtually equivalent to a flat-plate unit. In the case of imaging collectors another aspect which plays a crucial role is the specularity and accuracy of the surface figure of the collector. If the reflector is not perfectly specular the image is defocussed; similarly if the surface is not exactly configured, defocussing or spreading of the image occurs, with the result that all the reflected radiation may not end up at the absorber, whose dimensions may be inadequate to accept the defoccused image. There are various ways of estimating the extent of this error if the surface inaccuracies are specified. Another aspect concerning high temperature devices is the extent of radiation loss. With increasing temperature of absorber the radiation loss goes up as the fourth power of T while convection goes more or less linearly. So, if the absorber has a mere black painted surface (emissivity, $\varepsilon \simeq 0.9$) then radiation losses would prevent T from going high. Another parameter is the flow rate of the heat transfer fluid that is carrying away the useful heat. The permissible flow rate for the fabricated unit has to be estimated and then the proper flow rates used.

As an initial step, a careful design of the system experiment is to be made, and then after the system has been fabricted a study is to be made to see where there are discrepancies between the design parameters and the actual fabricated device. Experiments should be performed and the performance analysis carried out in the light of the observations above.

7.2 Measurements of Solar Energy

The intensity of solar radiation can easily be monitored using any photosensitive device like, silicon solar cells, CdS cells or photo-transistors, etc. But these devices have limited

and non-flat spectral responses and temperature coefficients of response. So, for a given optical energy (say 1 watt) in say the blue region (400 nm) the response will be totally different from 1 watt in the red region (650 nm). The change in temperature (either ambient and/or device temperature due to absorption of radiation) will cause a change in output for the same input radiation level. This is why it is difficult to accurately interpret the output of the solar cell in terms of input radiation intensity. In the earlier issue of Perspectives a detailed description of the problems with this type of device were given both in chapter 3 and in the forum.

One simple solution is to calibrate the device in the sun along with a standard Pyranometer, although the temperature problem remains unsolved.

Another important point to be borne in mind when global irradiation is to be sensed, is that photo devices are inadequate, since, the encapsulation of the photo-cell within a case reduces the field of view, and most photo devices have a directional sensitivity.

7.3 Solar Stills

Solar stills are fairly simple devices to construct and operate. But as has been observed in the two projects carried out, the quantity of distillate collected is much below the expected values. The primary requirement for the operation of a solar still is that there be a region which is totally enclosed and airtight with no ingress or escape of ambient air. If this condition is not satisfied the vapour produced at the surface of the water pool does not condense on the roof. The mechanisms operative in the still are diffusive, and natural convection transports the vapour from the saturated warm surface to the cooler condensing roof. Attempts at increasing the surface of evaporation by the incorporation of wicks have not been very successful. On the other hand increasing the temperature of water of the warm

surface and reducing the roof temperature will yield beneficial results.

7.4 Solar Refrigerators

Absorption refrigeration has been attempted in many projects without any interesting results. In a forth-coming volume a study of solar refrigeration cooling will be presented. It is sufficient to state here, that the COP of an absorption refrigerator is normally low (being about 0.5 or so), but when a solar flat-plate collector ($T \leq 80°C$) is used this falls to even lower values (0.1 or less). A thermodynamic analysis is to be carried out in detail to estimate the expected performance, and in this analysis the energy required for circulating the fluids is also to be taken into account.

Any project attempting solar refrigeration should bear in mind that it is a very time consuming job and it cannot be expected to be completed within one semester.

7.5 Solar Pumps

A very interesting innovation of using rubber bellows in the fabrication of a water pump has been attempted. Unfortunately no results have been presented. As a first exercise a thermodynamic analysis of the device has to be carried out to obtain an estimate of the upper limit of performance that is possible. In the case of the jet pump concept, it is well known that the efficiency of such devices hardly ever reaches 0.5%. But as exercises in design, fabrication and analysis these are good problems to tackle, once the basic limitations are realized.

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8. Review of SPP Projects on Solar Energy

8.1. College: M.S.R.C.E., Bangalore

Project:

Solar Water Pump (Stage 1) - Design and fabrication of low pressure turbine.

Year: 1978-79

Objective

To fabricate a low pressure turbine for solar water pumping.

Specifications

The turbine has been designed to operate at an air pressure of 1.1 to 1.5 kgs/cm^2.

Methodology

Different types of pumps (centrifugal, reciprocating and steam jet pumps) and turbines were studied. The merits and limitations of various pumps for solar energy application were examined. A low pressure turbine-reciprocating pump combination was considered suitable for solar pumping. As a first step, the design and fabrication of a low pressure turbine was taken up.

Description of the Equipment:

The device consists mainly of a rotating member with four arms. The arms are hollow tubes with rubber bladders at their ends. The rotating member is mounted horizontally in a casing

such that one of the arms is immersed in the water contained in the casing. An inlet pipe leads air at a pressure of 1.1 to 1.5 kgs/cm^2 into the arm (arm 1) immersed in water. The bladder moves upwards, thereby turning the rotating member 90°. This brings arm 1 to the surface of the water and another arm (arm 2) to the position previously occupied by arm 1. Air from the bladder of arm 1 now escapes to the outside through n aoutlet pipe. Now the inlet pipe communicates with the port on a rotating member which leads to arm 2. Pressurised air enters arm 2 and the cycle is repeated. (An arrangement on the rotating member automatically brings the inlet and outlet pipes into communication with the ports, on the rotating number, which lead to the arm immersed in water and the arm at the water surface with inflated bladder).

Performance figures

No performance studies have been carried out.

Comments

1. The turbine has not been designed for a specific output. No design details have been presented. This makes it difficult to know whether the weight of arms, hydrostatic pressure on the bladders etc., have been taken into consideration or not.

2. The turbine has been designed to drive a reciprocating pump. Owing to the large friction between the turbine at the bearings and the pump, the device may not work at all.

8.2. College : S.I.T., Tumkur

Project : Solar Pump

Year : 1979-80

Objective

To design and fabricate a solar pump.

Specifications

The pump is not designed for any specific output. The pump body is made of galvanized iron pipes of diameter 1'' and 2''.

Methodology

1. Different devices used to exploit solar energy were studied.

2. A detailed study was then made of the different pumps (such as photovoltaic pumps, savery pumps and passive pumps) considered suitable for solar energy applications.

3. Based on these studies, the modified savery pump was selected. The pump was fabricated and tested using steam produced in a boiler.

Description of the Equipment

The pump has evaporating and condensing sections. In the evaporation section, water is converted into steam using solar energy (in the experiments conducted at SIT, a steam boiler served as the evaporating section). The condensing section and its working are described below. The condensing section consists mainly of a 2'' G.I. pipe placed vertically in a water tank. The top end of the pipe is closed with a gate valve. The vertical pipe has two G.I. pipes of small diameter (1'' each) attached to it at different heights from the bottom of the tube. The tube makes an angle of 90° with the main pipe. The lower pipe leads steam from the evaporating section to the main pipe. The tube at a higher level acts as the delivery tube.

To begin with, the pump barrel (the vertical pipe) is filled with water so as to remove the air from the system. Steam is then passed through the lower pipe. When steam flowing at a particular velocity, strikes a water surface inside

the main pipe, it creates turbulence so as to initiate condensation. This creates a partial vaccum in the tube which causes water to be sucked into the main pipe, thereby causing a flow through the delivery pipe.

Performance figures

Volume of water pumped in 10 minutes=4 litres (about 25 litres/hour)

Weight of steam used=5 kgs per hour

Steam pressure=1.3 — 1.5 kgs/m^2

Delivery head=4 feet (about 1.2m)

Comments

1. The pump has a very low efficiency.

2. It has been stated that the pump stopped working after 20 minutes. Thus it is not suitable for continuous operation.

3. A boiler has been used to produce steam. In practice, a separate solar energy device should be built to obtain the required quantity of steam. It may not be possible to build a low cost solar device to continuously obtain 5 kgs of steam at 1.3 kgs/m^2.

8.3 College: B. E. C., Bagalkot

Project: Solar Oven

Ycar: 1980-81

Objective

To fabricate a solar oven.

Specifications

The oven uses 8 reflectors, made of plane silvered glass mirrors. 4 mirrors are of square type (50 cm × 50 cm).

4 mirrors are of the triangular type. The oven uses a hot box made of wood and covered on the inner side with aluminium foil.

Area of the glass cover $= 0.25\ m^2$

Protected Area of the reflectors and the glass cover normal to solar radiation $= 0.87\ m^2$

The cooker is designed to give a temperature of 250°C inside the hot box.

Methodology

Different types of solar ovens such as paraboloidal reflector type, cylindrical parabolar type and plane reflector type, were studied.

2. After examining the cost and constructional details of the various ovens, it was decided to fabricate a solar oven with plane mirror type reflectors.

3. A solar oven with plane mirror reflectors and a hot box was constructed and tested.

Description of the cooker

The solar oven employs an insulated (glass wool insulation) hot box with double glazing (50cm × 50cm) at its top and eight reflectors, made of silvered glass mirrors, four of square shape (50cm × 50 cm) and four of triangular shape. Cooking vessels can be placed inside the hot box.

Experimental results

The experiment was conduced on 26 December 1981 from 8 a.m. to 5 p.m. to determine the temperature inside the hot box. The maximum temperature inside the hot box was found to be 80° C, (temperature was measured using a thermocouple).

In another experiment, it was found that the time required to bake 300 gms of bread and 1kg. of cake was 4 hours.

Comments

1. The cost of the cooker is very high (Rs. 1,000)

2. Only one set of experiments have been conducted. The results show that the maximum temperature obtainable inside the box is around 80°C. Some more experiments have to be conducted to evaluate the performance of the cooker.

8.4. College: M.C.E., Hassan

Project: Solar Autoclave

Year: 1981-82

Objective

To design and fabricate a solar autoclave for sterilising medical instruments.

Specifications

The autoclave is designed to bring 2 litres of water from 25°C to 100°C in 30 minutes.

Projected area of the focussing collector = $0.64 m^2$.

Description of the autoclave

The autoclave consists of an aluminium cylinder (10cm diameter and height equal to 40 cms) welded to an aluminium disk at the bottom and covered at the top with an aluminium lid. The cyclinder is placed at the centre of a conical reflector. The truncated cone-type reflector (dia of the smaller end = 10 cm; dia at the big end = 90 cms) is made of strips. The conical reflector with the central cylindrical vessel can be placed on a stand made of M. S. angles.

Experiments and Results

Performance tests were conducted between 25 September and 27 September 1982. In these tests, about 2 litres of

water was placed in the cylinder and the whole unit was placed in the sun. The results are given below :

Date	Starting time	Ending time	Total duration	Initial temp. of water in the cylinder (°C)	Final temperature of the water (°C)
25-9-1982	1-30 p.m.	2-45 p.m.	1 hour 15 minutes	25	97
26-9-1982	11 a.m.	12 noon	1 hour	25	99
27-9-1982	12 noon	1-30 p.m.	1 hour 30 minutes	25	98

[The efficiency of the unit is about 40-45%]

Comments

1. The cost of the unit is very high (about Rs. 900/-). The major items which contribute to the cost are the stand and the conical reflector. Stand costs about Rs. 250/- and the cost of the reflector (excluding the cost of the mirror strips) is about Rs. 110/-. The stand could have been fabricated using wood instead of M. S. angles and the conical reflector could have been made of bamboo basket and paper mache instead of aluminium sheet.

2. The temperature obtained is about 99°C which is low when compared to the temperature (about 120°C) required for sterilizing medical equipment.

8.5 College : B.D.T., Davangere

Project : Solar autoclave

Year : 1981-82

Objective

To design and fabricate a solar autoclave for sterilizing medical equipment.

Specifications

The unit is designed to produce saturated steam at 120°C. It uses a conical reflector having an area of 2.65 m^2 (projected area of the reflector works out to be 0.85 m^2).

Mcthodology

A study of the availability of solar energy was initially made. Different devices used to exploit solar energy were then studied. Various types of collectors such as flat-plate collector and focussing collectors were examined. The advantages and limitations of different collectors were looked into. A solar autoclave using a conical reflector was designed, fabricated and tested.

Description of the autoclave

The autoclave consists of two coaxial aluminium cylinders welded to an aluminium disc at the bottom and covered with an aluminium lid at the top. The annular space between the two cylinders can be filled with water. The inner cylindrical chamber (also called sterilizing chamber) is equipped with thermocouples and air vent at the bottom which can be used for draining out the condensed steam. A wire mesh basket provided inside the autoclave holds the medical equipment. The cylinder assembly (autoclave) is placed at the centre of a reflector which consists of a truncated cone shaped bamboo basket with its inner surface covered with aluminized nylon plastic sheets. The entire assembly is placed on a stand made of M. S. angles.

Experiments and results

The annual space between the two cylinders is filled with 0.5 kg of water and the autoclave is exposed to solar radiation. The results of the experiments are given below.

Experiment conducted on 27 June 1982

Duration of the experiment=1 hour 30 minutes (From 2-30 p.m. to 4 p.m.)

Ambient temperature=32°C

Max. temperature of the sterilizing chamber = 70°C at 3-30 p.m.

Average temperature inside the chamber = 60°C

(Efficiency = about 5%)

Experiment conducted on 29 June 1982

Duration of the test=1 hour 30 minutes (from 2-30 p.m. to 4 p.m.)

Maximum temperature inside the chamber=68°C at 3.45 p.m.

Average temperature=59°C

Ambient temperature = 34°C

(Efficiency=around 4%)

Comments

1. The cost of the autoclave is high (about Rs. 1,200/-). The major items which contribute to cost are the reflector (Rs. 370/-) and the cylinder assembly (Rs. 250/-).

2. The autoclave has a low efficiency. As the temperature inside the chamber does not go above 70°C. The unit cannot be used for sterilizing medical equipment.

8.6 College: B. E. S. C. E., Bagalkot

Project : Tracking unit for sun basket

Year : 1980-81

Objective

Design and fabrication of a sun tracking unit for a parabolic concentrator (sun basket).

Specifications

The device tracks the sun at the rate of 0.00694 revolution/minute. It uses a 50 cm. simple pendulum as the timer.

Performance figures

In this device, a clock mechanism (spiral spring - gear train - pendulum combination) has been used to give uniform angular motion to a sun basket. A spiral spring supplies the energy needed to drive a gear mechanism (a gear train consisting of 10 gears). The gear train is used to achieve the desired speed reduction. A pendulum acts as the timer.

The device performs well when used with the sun basket type cooker.

Comments

The device costs about Rs. 1,500/-. This is about three times higher than the cost of the sun basket. The major items which contribute to the cost are the gear train (cost about Rs. 700/-) and the bearings (cost about Rs. 300/-). In order for the device to be useful, the cost should be reduced to about Rs. 150/- (because of its high cost, a tracking device is normally not used for such devices as solar cookers and stills).

8.7 College : J.C.E., Mysore

Project : Solar Intensometer

Year : 1980-81

Objective

To design and fabricate a solar intensometer for measuring the intensity of solar radiation.

Methodology

A detailed study of the availability of solar energy was initially made. Various devices used to measure the different components of solar radiation were then studied. These include pyranometer, shaded ring pyranometer and pyrheliometer. The importance of sun-tracking and the various methods of achieving

tracking were discussed. Different photosensitive devices such as the phototransistor, photoresistor and solar cell were studied. A solar intensometer making use of a phototransistor was then designed and fabricated.

Description of the intensometer

The device consists of (i) a mechanical system for achieving sun-tracking and (ii) an electrical system for measuring solar insolation.

The mechanical system is driven by a synchronous motor running at 1 rpm. A gear train consisting of 9 gears is designed to achieve the desired speed reduction (1/1440). A crank and eccentric mechanism converts the rotary motion of the gear train output shaft into oscillator motion of a crank. The photosensitive transistor placed at the end of the crank follows the sun at the rate of 15° per hour. A cone and lens arrangement focusses the light beam onto the phototransistor.

The electrical system consists of a phototransistor, a power supply for biasing the transistor and a galvanometer calibrated to measure solar insolation.

Calibration

The intensometer was calibrated using a photometer. A standard bulb of 60 watts, 230 volts was used to illuminate the inside of the photometer. The detector assembly, consisting of cone and lens arrangement and the phototransistor was kept inside the photometer. The light intensity inside the photometer was varied by changing the voltage applied to the bulb using a variac. For different values of input voltage applied across the bulb, the current flowing in the transistor circuitry was noted down. A table was then constructed to give the relationship between the collector current and the power dissipated in the transistor circuit.

Comments

1. The experimental set up used for calibration has not been described. Exact details regarding the procedure adopted for calibration have not been presented.

2. The instrument has not been used to measure solar insolation.

8.8 College: B.M.S.C.E., Bangalore:

Project:

Development and Fabrication of Solar Milk Pasteuriser.

Year: 1979-80

Objective

Design and construction of solar milk pasteuriser.

Specifications

Parabolic cylindrical
concentrator — length of the aperture = 100 cm
width of the aperture = 100 cm
focal length = 25 cm

Capacity of the pasteuriser = 4 litres/hr (or about 25 litres/day) Final temperature 72° C.

(Efficiency works out to be 31%)

Performance figures

The device uses a parabolic cylindrical concentrator to focus light on to an absorber pipe through which milk flows. The device has been designed to heat milk to a temperature of about 72° C. Milk coming out of the absorber pipe is held at that temperature for about 15 seconds in the holder unit and then cooled to about 4° C in an ice box.

Experiments were conducted on 13 April 1980. Results are as follows:

Duration of the test: 6 hours (from 9 a.m. to 3 p.m.)

Average ambient temperature: 32° C.

Average solar insolation: 740 kwl/m^2 hr.

For a flow rate of about 2.6 litres/hr, the temperature of milk at the outlet was about 90° C (Efficiency 21%)

The outlet temperature decreases to about 75°C when the flow rate is increased to about 3.6 litres/hr. (This is quite close to the designed performance. Efficiency works out to be 22%).

Special features: Nil

Comments

The efficiency of the unit is quite low (about 21%)

8.9. College: K.R.E.C., Surathkal

Project:

Solar Refrigerator (Intermittent vapour absorption refrigeration cycle)

Year: 1979-80

Objectives

Design and fabrication of a solar ice making unit.

Specifications

1. Capacity=6 kgs of ice/day
2. Flat-plate collector area=2.16 m^2
   (Coefficient of Performance of the unit=0.16)

Performance figures

The unit makes use of NH_3-NaSCN combination (6 kgs of NaSCN and 5 kgs of NH_3) for producing the refrigerating effect.

A flat-plate collector acts as a generator-absorber and another vessel connected to the flat-plate collector by means of G. I. piping, acts as a condensor-evaporator. The generator-absorber containing NH_3-NaSCN solution is exposed to the solar radiation during a day cycle of about 5 hours. NH_3 evaporates from the solution and is condensed and collected in the condenser. During the night cycle, the condensate evaporates taking heat from the surrounding space. The vapours produced are again absorbed by the NaSCN solution. The performance test conducted on the 29 February 1980 gave the following results :

Generation period = 5 hours (9 a.m. to 2 p.m.)

Refrigeration mode = 2 hours

Minimum temperature of water = 3°C

Quantity of water = 8 litres

Ambient temperature = 30°C

Technological innovations

The system uses NH_3-NaSCN combination. NaSCN has good absorbent properties such as high solubility at low temperatures, low solubility at high temperature and very low vapour pressure at room temperature.

Comments

The actual COP works out to be 0.05 which is very low.

8.10 College : S.I.T., Tumkur

Project : Solar Refrigerator

Year : 1978-79

Objective

Design and fabrication of a solar refrigerator.

Specifications

1. Refrigerator capacity : 1/50 ton
2. Collector area : $1.58 m^2$
   (C.O.P. works out to be about 5.5)

Performance figures

An electrolux refrigerator has been converted into a solar refrigerator using a flat-plate collector. Tests conducted on the 4 & 5th of July 1979 form the following results :

Rise in collector temperature = 16°C

Refrigerating effect = Nil

Technological innovations

Nil

Comments

1. For a refrigerating effect of 1/50th of a ton, the collector area has been worked out as $1.58 m^2$. On a dull day, the C.O.P. works out to be about 5. This is an unrealistic figure as far as refrigerators are concerned. (The C.O.P. varies from 0.1 to 0.3).

2. An electrolux refrigerator has been unnecessarily used. The collector could have been used as the generator-absorber with another vessel serving as the evaporator-condenser. This would have considerably reduced the cost of the equipment and would have, probably, given good results.

8.11 College : N.I.E., Mysore

Project : Design of cold storage unit using solar energy

Year : 1978-79

Objective

To design a 2-ton, solar powered continuous absorption system using ammonia-water combination for cold storage applications.

Methodology

1. The cooling load was calculated by assuming the weight of food stuff to be stored as 2000 kgs and the dimensions of the cold room as 3m × 3m × 3m.

2. Thermodynamic analysis of the proposed system was carried out. After considering various refrigerant-absorbant combinations, it was decided to design a system using ammonia-water combination.

3. Different system components such as collector, condenser, evaporator, heat exchangers and rectifier were then designed.

Design Specifications

A solar flat-plate collector of tube-in-sheet type has been designed. This collector area works out to be $30m^2$. The collector can deliver 588 kg of hot water at 75°C per hour. The generator is of shell-and-tube type. The solution temperature in the generator is expected to be 75°C. The condenser is of 2-pass shell-and-tube type with 14 kg/cm^2 working pressure. The absorber is a vertical tube-type heat exchanger. Two liquid - to - liquid heat exchangers of tube - in - tube type have been designed. (One heat exchanger is placed between the absorber and the generator). A cold chamber of 3m × 3m × 3m size has been designed. The evaporator consists of a finned tube placed in the cold chamber. The temperature inside the evaporator is expected to be 5 to 10°C, the temperature inside the cold chamber is expected to be around 5°C. The evaporator pressure is around $33kg/cm^2$. Two pumps are required to pump NH_3-H_20 solution and hot water.

Working

The generator, the condenser, the evaporator and the absorber are connected to form a closed loop. The working of the system is explained below.

In the absorber, weak ammonia solution is exposed to ammonia vapours coming from the evaporator. The weak solution absorbs ammonia and the resulting strong solution is pumped into the generator. In the generator, heat is added to the strong ammonia solution. (Hot water delivered by the collector gives off its heat to the ammonia solution). The heat vapourises the ammonia, and the vapours are condensed in the condenser. The ammonia liquid at high pressure is passed through an expansion valve into the evaporator. In the evaporator, the liquid gets vapourised by taking heat from the surrounding space and the vapours pass into the absorber. The weak solution left in the generator after the ammonia has been driven off flows through a reducing valve back to the absorber.

Comments

1. Design details for the generator have not been presented. Moreover, the pump capacity, capacity of the receiver and the design details for the absorber have not been worked out.

8.12. College: K.R.E.C., Surathkal

Project:

Utilisation of solar energy for refrigeration purpose (A theoretical design)

Objective

To design a 1-ton intermittent vapour absorption solar refrigeration system.

Methodology

1. Initially, a detailed study was made of vapour absorption type of refrigeration cycles. Intermittent and continuous vapour absorption cycles were discussed.

2. The possibility of utilizing solar energy for refrigeration purposes was examined.

3. Various attempts made in different countries at utilizing solar energy for refrigeration purposes were reviewed.

4. A comparative study was than made of refrigeration systems using different refrigerant-absorbent combinations such as ammonia-water, water vapour-lithium bromide solution and ammonia-sodium thiocyanate solution.

5. After examining the advantages and disadvantages of using various refrigerant-absorbent combinations, it was decided to design a system using ammonia-sodium thiocyanate solution combination.

6. Detailed thermodynamic analysis of the system was carried out.

7. Different system components, such as flat-plate collector (generator-absorber), storage tank and condenser-evaporator were then designed.

Design specifications

The system uses (i) flat-plate collector, which serves as the generator-absorber, (ii) a condenser-evaporator and (iii) a storage tank.

Flat-plate collector (Generator-absorber) :

10 collectors,each having an area of $2.22 m^2$ (total area $= 22.2 m^2$)

Collector solution temperature $= 95°C$

The collector is of tube-in-sheet type and contains ammonia solution.

Condenser-evaporator :

A cylindrical vessel (28 cm dia and 42 cm height) is placed inside a steel jacket (40cm dia, 85cm height) containing water.

Condenser temperature$=40°C$; Evaporator temperature$=5°C$.

Storage tank :

Cylindrical tank of 75cm dia and 125cm height.

Working

The collector is connected to the condenser/evaporator through the storage tank. There are two pipe lines, between the collector and the condenser/evaporator. One of the pipes, fitted with a valve V_1, carries ammonia vapours from the collector to the condenser during the day cycle. The second pipe, fitted with valve V_2, carries ammonia vapours from the evaporator to the collector, during the night cycle. The working of the system is as follows :

During the day cycle, the collector is exposed to solar radiation with the valve V_1 open and V_2 closed. Due to solar heating, the ammonia solution gives off ammonia vapours and the vapours are collected and condensed in the condenser. During the night cycle, the valve V_2 is kept open and the V_1 is closed. The glass cover of the collector is removed. The liquid ammonia in the evaporator gets evaporated by taking heat from the surrounding space. The ammonia vapours, are reabsorbed by the weak solution in the collector, while the heat of absorption escapes from the collector surface.

Comments

In designing the condenser/evaporator, only the volume of ammonia to be condensed has been taken into account and the heat transfer has not been considered.

8.13 College : S.I.T., Tumkur

Project : Solar Refrigeration using zeolite

Year : 1981-82

Objective

To study the feasibility of using zeolite for solar cooling applications.

Methodology

Initially, a detailed study was made of different vapour absorption refrigeration cycles commonly used for solar cooling applications. The drawbacks of conventional cycles using ammonia water and water vapour-lithium bromide solutions were discussed. The suitability of zeolite absorbent in solar refrigeration cycles was discussed. Data regarding the availability of zeolite in India were collected. An experimental set-up was designed and fabricated. The set-up could be used to conduct experiments to determine the absorption properties of zeolite available in India.

Description of the equipment

The experimental set-up consists mainly of (i) a zeolite panel, (ii) a condenser-evaporator and (iii) a storage tank. The zeolite panel (30 cm $\times$ 30 cm $\times$ 5 cm) is made of G.I. sheet and it can hold about 0.5 kg of zeolite. The panel is painted black for maximum absorption of solar radiation. It communicates through an ordinary G.I. pipe with a condenser-evaporator. The condenser-evaporator is of air cooled type. Because of very low flow rates inside the system, the condenser-evaporator is made of a single copper pipe, 1 cm diameter and 1.5 meter long. The condenser-evaporator is connected by means of a flexible piping with a storage tank. The storage tank is nothing but a graduated bottle capable of holding about 250 cc of water. After placing zeolite in the panel, the entire system is sealed and evacuated.

Experiments and results

The experimental set-up was constructed with the intention of conducting experiments to determine (i) mass of water desorbed from the zeolite kept in the panel, and (ii) to determine the cooling efficiency of the system. However, such tests were not conducted because of difficulties encountered in evacuating the system.

Conclusions

Conventional refrigeration cycles using ammonia water vapour-lithium bromide solution are inefficient for solar energy applications. The efficiency of such units rarely exceeds 20%. Many attempts have been made to find a suitable absorbent to replace conventional absorbents. An attempt made in this direction at Masachusetts Institute of Technology, U.S.A. utilising zeolite as a sorbent has proved successful. Systems using zeolites like chabazite or clinoptilolite have been found to attain efficiencies of the order of 50%.

The efficiency of a system using zeolite, however, is found to depend on such factors as the heat of adsorption of zeolite for a particular refrigerant, adsorption capacities for refrigerant and desorption temperatures. Systems constructed at MIT have used zeolites like chabazite or clinoptilolite. The properties of these zeolites are well known and these zeolites have proved ideal for solar refrigeration. However, the picture in India is totally different. Zeolites like chabazite are not found to occur in quantities exploitable for large scale applications. Only less known varieties such as seolectic, stilbite and natrolite are found to occur in abundance. But a lack of information about the properties of these zeolites does not at present permit the utilization of these zeolites for large scale solar energy applications. It is therefore necessary to undertake detailed investigation to get a thorough acquaintance with the properties of the zeolites found to occur in India. Only then can full scale systems for solar energy applications be constructed.

Comments

1. No experiments have been conducted with the designed set-up. As the system is designed for zeolite-water combination, a very high vacuum should be produced for the operation of the system. Some other combination such as zeolite-ammonia or zeolite-sulphur dioxide combination which does not require a high vacuum could have been used.

2. Exact details regarding the availability of zeolite in India have not been presented.

8.14 College: M. S. R. C. E., Bangalore

Project : Modified Solar Still

Year : 1978-79

Objective

1. Conducting experiments to compare the performance of a water lens - flat-plate collector combination with that of an ordinary flat-plate collector.

2. Design and fabrication of a solar still to make use of water lens flat-plate collector combination.

Specifications

1. Effective area of water lens = 2500 cm^2

2. Effective area of the focus = 600 to 900 cm^2

3. The still is designed to produce about 6 litres of potable water per day.

(Efficiency works out to be about 67%)

Performance figures

(i) Experiments to compare the performance of water lens-flat-plate collector combination and an ordinary flat-plate collector :

In these experiments, an ordinary flat-plate collector and a water lens were used to evaporate a fixed quantity of water. For these experiments, a black cloth soaked in salt water was used. In some experiments the black cloth was folded into eight folds and kept at the focus of the water lens; while in others, the cloth was cut into 8 pieces and the pieces were kept at the focus and were replaced as soon as they become dry. The results of these experiments are as follows:

Area of water lens (m^2)	Area of cloth used in water lens solar stills (m^2)	Area of cloth used in flat plate solar still (m^2)	Mass of water (Kgs.)	Time taken for drying the cloth (minutes)	
				For water lens	For flatplate Collector
0.1964	0.1964	0.1964	0.040	55	20
0.1964	0.0189×8	0.1964	0.015	23	5

(ii) Experiments with the water lens solar stills:

Experiments were conducted to measure the quantity of distillate produced in a specified period of time. The results are as follows:

1. Test conducted on: 8 May 1979

   Water evaporated—3 litres in 2 hours

   Distillate collected—a few ounces

2. Test conducted on: 1 June 1979
   Water evaporated—about 1 litre in 3 hours 30 minutes
   Water collected—1/2 litre

3. Test conducted on: 10 June 1979
   Water collected = 0.75 litres in about 4 hours

Technological innovations

The still makes use of a rectangular water lens (made by placing water on a PVC sheet fastened to a rectangular wooden

framework) to focus a beam of light on an ordinary flat-plate collector.

Comments

1. In experiments (i) the results do not clearly show whether a water lens collector combination gives a superior performance over that of an ordinary collector or not. (They seem to point to the contrary).

2. The actual performance of the still comes nowhere near the designed performance. It is stated that only a few ounces of water were collected in about three hours. This is a very poor performance.

8.15. College: B.E.C., Bagalkot

Project: Design and fabrication of solar still

Year: 1979-80

Objective

Design and fabrication of solar still (Single slope type)

Specifications

1. Area of the basin $= 1.08 m^2$

2. It has a capacity of 3 litres of potable water per day (efficiency assumed to be 30%).

Performance figures

Tests were conducted by keeping the still in the sunlight for about 7 hours/day on the average. (From September 18, to September 29, 1980). In some of the trials, a black painted corrugated G. I. sheet was placed at the bottom of the still. It was thought that this would increase the effective area exposed to the sunlight, thereby increasing the efficiency of the still. The results of these tests are summarised below.

Hourly yield of distillate (when corrugated sheet was not used)	152.55 ml
Hourly yield of distillate (when corrugated sheet was used)	111.00 ml

Technological innovations

Use of corrugated G. I. sheet to increase the effective collector area which was painted black.

Comments

1. The yield works out to be about a litre per day, which is very low for the given basis area of 1 m^2. In the experiments, the water depth in the still was maintained at 10 cms. (The depth should be lower than 5 cms). This may partially account for the low yield.

2. It was thought that by using a corrugated sheet the yield would increase. However, the results point to the contrary.

3. The wooden box costs too much (Rs. 300/-). In addition to this, a tank having the same dimensions as the wooden box has been fabricated out of G. I. sheet. This unnecessarily increases the cost. A small tray constructed from G.I. sheet would have been sufficient.

8.16 College: S.I.T., Tumkur

Project: Solar still

Year: 1978-79

Objective

Design and fabrication of a solar still for producing potable water from saline water (double slope type still).

Specifications

1. Basin area: 1.26 m^2

2. Capacity: 4 litres of distilled water per day (about 8 hours) (Efficiency: about 43%)

Performance figures

As no tests were conducted, performance figures are not available.

Technological innovations: Nil

Comments

1. The cost of the still is around Rs. 900/- This is too high for a designed capacity of 4 litres. Nearly Rs. 400/- has been spent on fabricating the box and the trough (G.I. sheet is used for construction). The cost could have been reduced by selecting a single slope type design and by constructing the box out of wood.

8.17 College: M.S.R.C.E., Bangalore

Project: Solar still

Year: 1977-78

Objective

Design and fabrication of a solar still

Specifications

Basin area = 1.15 m^2
(Glass cover area = 1.3 m^2)

The still is designed to produce 3-4 litres of potable water per day (efficiency about 45%).

Methodology

1. A brief survey of availability of solar energy and the possibility of its utilisation with particular reference to solar stills was carried out.

2. The mechanism of working of a solar still was studied.

3. A solar still was designed and fabricated.

Description of the still

The still is of single slope type and consists of a frame work and base of size 1.95 m × 0.6 m. The cover is an ordinary 3 mm window glass, inclined at an angle of 23° to the horizontal. The still uses polyethylene trays to hold saline water. A G.I. channel attached to the framework conveys the condensate to a storage tank.

Performance figures

Tests were conducted between 3 June and 13 June 1979. The results are as follows:

Test conducted on 3 June

Quantity of water placed in the tray at the beginning of the test—1.5 litres (at 12.30 p.m.); Quantity of water present in the tray at 5 p.m.—Nil; Volume of condensate collected – Nil

Test conducted on 5 June

Volume of water placed in the tray at 9-15 a.m.—2.5 litres Volume of water present in the tray at 2-30 p.m.—Nil; Volume of condensate—a few milli litres

Test conducted on 13 June

Volume of water placed in the tray at 9 a.m.—5 litres; Volume of water present in the tray at 12-30 p.m.—3 litres; Volume of condensate—1.5 litres

Comments

1. The still has been designed to produce 3-4 litres of distillate per day. However, the test results clearly indicate that the actual performance is far inferior to the designed performance.

9. Forum

This forum attempts to address both the students and the faculty on topics covered by the "Perspectives in Technology". Questions may be addressed to Editor, Perspectives in Technology, KSCST, I.I.Sc., Bangalore-560 012.

Question :

1. Which is the ideal fluid for solar collectors?

Answer :

There is no single ideal fluid for solar collectors. As could be expected the task that is to be performed demands some properties which may not all be fulfilled by a single fluid. Water is an excellent fluid for most purposes, since its heat capacity is the largest of all liquids ($c_p = 1$ kcal/kg°C), its thermal conductivity is also large ($k = 0.6$ W/m°C) its viscosity is also moderate ($\mu = 8.6$ kg/m.sec) as compared to other heat transfer fluids. Further the phase transition temperatures of water are well suited for use with flat-plate collector devices. But water is a fairly difficult substance to handle in many of the collectors because of its corrosive nature. With aluminium or mild steel, collectors corrosion is the single main limiting consideration. When copper is substituted for aluminium or mild steel the corrosion problem is greatly alleviated. Plastic collectors capable of operating at elevated temperatures can ofcourse handle water much better. If however the ambient temperatures fall below the freezing point of water antifreeze compounds like glycols—ethylene or propylene glycol, can be

Table 9.1

Materials	Specific Heat (C) J/m^3K	Thermal Cond. (k) W/m. K	Density g/m^3	Viscosity m^2/s	Thermal Exp. Coeff. K^{-1}
Water (82°C)	4190	0.640	1000	.0035	.00018
Glycol (82°C)	3630	0.415	1020	.01–.02	.00054
Silicon Oils (82° C)	1480	0.140	930	.005–.01	.000108
Hydrocarbon Oils (82°C)	1770	0.121	880	.001–0.1	.00054–.00144
Glycerin (50°C)	2583	0.287	1245	.00015	.0005
Dowtherm J (37.8°C)	1968	—	—	—	—

added to lower the freezing point to as low a value as—50°C. On the other hand if temperatures higher than the boiling point of water are required either pressurised water systems or steam could be utilized.

An interesting application is where an engine working in conjunction with a solar flat-plate collector is desired. Since the peak temperatures encountered with flat-plate collectors is rather limited (80 to 120°C) water or steam would not be satisfactory as working fluids. In such cases organic fluids like freons or other refrigerant fluids are better suited since their boiling points are much lower.

Air is another fluid that is used especially if drying or space heating is required. If heat storage is required, some other medium such as pebbles or water is to be used, since the heat capacity of air is very small.

Several other fluids have been tried or proposed as working fluids for solar collectors. Table 9.1 shows the properties of some of these fluids.

Question :

2. How does one compute the area of solar collectors required for a particular task ?

Answer :

The first step in this is to specify the task in terms of the energy requirement. For example, let the task be one of supplying 1000 litres/day of hot water at 60°C at Bangalore. Then the energy required is $mcp \triangle T = 1000 \times 4.2 \times (60-25) =$ 147,000 KJ/day, when the initial temperature of water is 25 C. The next step is to select the type of solar collector. Here one evaluates the collectors available in the market and chooses the appropriate device (see next question for more

on this). Once the collector is chosen its performance (or efficiency) at the desired temperature is found either from first principles [1] or from the manufacturer's specification or by experiment. The average solar insolation for all the months at the locale (Bangalore in the example) is obtained from meteorological data books. If this is not readily available an estimate is to be made of the insolation. Afterwards the orientation of the collectors (i. e., tilt) is to be decided. In this example the demand is constant throughout the year. This means that the maximum area of collectors required would be for a period when the solar insolation is a minimum. The insolation is a minimum during the monsoon period of July-Aug (Here the average values are kWh/day on a horizontal surface). Various tilt angles can be proposed for the collector until the maximum collection results during the critical months. For this tilt it should be checked whether the collection for other months will be equal to or greater than the demand.

In the winter months the collection increases with tilt while in the summer months the collection increases by reducing tilt. For the best annual collection the optimal tilt angle is $\beta = L + 10^\circ$, facing south. For the example cited, in the month of July, it is found that the best tilt is $L + 5^\circ$. Then the collection per day per square meter of collector is 4.59 kWh or 16,524 KJ. Thus the area of collector required is 25 sq.m. This is rather high. If one is content to design the system to provide all the hot water during the winter months then the best tilt is $L + 30^\circ$, and the collection is 21, 632 KJ/m/day or the collector area is 19 sq.m. If on the other hand the overall annual yield is optimised then the tilt is to be $L + 10^\circ$ or 23 degrees. The collection will then be 21,144 kJ/m and area is 20 sq. m. Here the efficiency of collector is computed first to be 35%.

It is thus seen that there is no unique answer, but an answer which is to be optimised on the basis of other considerations like cost, effectiveness, etc.

Question :

3. How is the efficiency of a collector measured?

Answer :

The efficiency of a collector is defined as

$$\eta = \frac{\text{useful energy collected}}{\text{solar radiant energy incident}}$$

This can be an instantaneous value or an hourly value or a daily or annual average. Since, the solar energy incident changes with time, location, season, and also tilt of the collector, the denominator is a variable. The numerator is affected by a loss factor U, (which depends on the materials used for the collector, thickness of the insulation, number of glass layers used, emissivity of absorber surface, wind velocity, etc) the $\alpha\tau$ values of glazing, and the absorber fluid inlet temperature.

For measuring the efficiency unambiguously the test conditions should be steady. To ensure this, the test procedure proposed is to keep the collector in an enclosure exposed to a solar simulator (a bank of lamps) and a constant flow of air over it (to stimulate wind). Fluid at a specific temperature is sent through the collector and its temperature rise is recorded. Unless this method of testing is utilized, the results would be ambiguous. The NBS and ASHRAE have specified detailed standards of the test procedure to be followed for determining the efficiencies (See for example 'Solar Age' Aug 1983).

Question :

4. How is a collector chosen for the task?

Answer :

It is possible to lay down the requirements of task as described in the question 2 above. The other constraints like, the area available where collectors can be situated for collecting unobstructed solar radiation, the life expectancy of collectors and the available budget, are to be specified. The

cost, performance and life of a collector are correlated in a rough manner. In the majority of cases a high performance collector will cost more and if a longer life is required the cost would again be high. For example, an all plastic collector could be the least expensive but its performance and life would also be the lowest. A mild steel collector would be of modest cost while the copper collector would be very expensive and have a better performance.

The choice of collector then involves an estimate of the cost of energy collected. For collecting the same amount of energy one would need more area of lower performance collectors entailing a larger number of collectors. But since their cost is also lower, one has to perform a comprehensive cost-benefit analysis before arriving at a conclusion. The parameters involved here are the initial (or capital) cost, the rate of interest, the cost of energy collected by the system, inflation rate, maintenance etc. Here, for example, if a mild steel collector costs Rs. 2000/= and has an efficiency of 35% while a copper collector costs Rs. 4000/= with efficiency of 42%, the energy collected by the two collectors is 766.5 and 920 kWh/year or Rs.383 and 460/year energy collection (at Rs.0.50/unit), without any interest and maintenance or inflation the payback period is about 5.2 years for the MS collector and 8.7 years for the copper collector. But if 16% interest, 2% maintenance and 8% inflation is assumed the payback period is 6.7 and 26 years respectively.

It is seen that although copper collectors have a better performance, their returns are lower since, the increase in performance is not exactly offset by increase in cost. But in terms of life expectancy mild steel collectors are definitely inferior.

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4. Total Air Conditioning by solar energy - Introducing the Clisotos house at Sophia Antipolis (French Alps) - Department Energies Nouvelle, Total Mines Nucleaire, Campagnie Francaise des Petroles, 5, Rue Michel - Ange 75781 **Paris Cedex 16**

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23. Mullick Subhash Chandra: Utilization of Solar Energy, Mechanical Engineering Monograph Series, III., Madras 36

24. Components of Solar Energy Systems. Solar Research Division of Refrigeration Research, 525, N. 5th St., Brighton, Michigan 48116

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NEXT ISSUE

The third issue of "Perspectives in Technology" will be devoted to Wind Energy and Wind Energy Devices. Articles are invited from students and faculty. The best article will be published. Students are also requested to pose their doubts on Wind Energy and Wind Energy Devices. Articles and questions should be addressed to the Editor, Perspectives in Technology, KSCST, Indian Institute of Science, Bangalore-12. The last date for receipt of articles and questions is 31st October 1984.

Notes on Preparation of Articles/Papers for Perspectives in Technology

Articles from faculty and students of the engineering colleges are invited. These articles should not exceed 3,500 words, and should be submitted in triplicate. They should be typed double spaced on A4 size paper. All figures including photographs should be numbered consecutively in arabic numerals in the order of appearance in the text. References should be cited in the text, by serial number. References should be listed at the end of the paper in the following format: Authors name, initials, year of publication, title of publication, publishers. Articles/papers should be addressed to the Editor, Perspectives in Technology, KSCST, IISc., Bangalore-560 012.

Perspectives in Technology contains a listing of books, reports and documents available at the KSCST or ASTRA libraries, on the sector under consideration. Students and faculty of the engineering colleges may use this material, at the KSCST and ASTRA libraries at Bangalore.
